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ASSESSMENT OF THE RELATIONSHIPS AMONG HYDROGRAPHIC CONDITIONS, MACROPOLLUTION HISTORIES, AND FISH AND SHELLFISH STOCKS IN MAJOR NORTHEASTERN ESTUARIES

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NOTICE

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ABSTRACT. This report covers analyses completed by use of macropollution variables, which are defined as aggregated variables that may indirectly represent trends in pollution by representing human-related (anthropogenic) activities or general water quality. Data were collected for five major northeastern estuaries -- Hudson River/Raritan Bay, Potomac River, Delaware River/Bay, Connecticut River, and Narragansett Bay for the period 1880-1980. These data included information on landings, fishing effort, hydrographic conditions, and pollution conditions for each estuary.

Methods developed to analyze historical stock-abundance time series used multiple lag times generally longer than one year. Categorical time-series regression permits analysis of time-series data in a framework that reasonably reflects the realities of fisheries biology (e.g., multiple-aged fisheries). Central to our method is the partitioning of independent variables into categories according to the number of variates and the qualitative levels each variate may assume. Once the categorical variables are formed, the analysis proceeds as for an ordinary least-squares computation. The functional forms of the progressive categorical-regression models are unspecified: only the number of linear regressors increases with the inclusion of new time series. Thus, models having a larger number of independent variables can be statistically compared to lower-rank models by use of full-and-reduced F tests.

Categorical regressions were run sequentially for all target stocks in each estuary using lagged stock (i.e., a variable representing the time lag between spawning and recruitment into the fishery), and hydrographic and macropollution conditions at the time of spawning and/or early development.

Historical stock variation was accounted for in the above stepwise manner. One central hypothesis concerning the analytical method is that "pollution" effects cannot be determined from historical series unless variation resulting from local hydrographic conditions is first accounted for. This proved to be the case for all macropollution variables except monotonic trend variates such as human population. Relationships between macropollution and stock abundance for variates including dissolved oxygen, dredging, and biochemical oxygen demand were much stronger if the residual part of the stock time series related to climatic conditions was removed. This phenomenon may account for the general lack of earlier evidence of such historical pollution-stock relationships.

1. INTRODUCTION

1.1 Background

Estuaries are highly productive environments that provide important habitats for commercial and recreational fish species. The estuaries and coastal regions of the northeastern United States (Chesapeake Bay to Narragansett Bay) historically have supported a large commercial fishing industry. However, significant variations in annual commercial landings from these areas are common, and landings of some important fisheries have declined greatly in recent years.

The effects of fishing and of environmental factors on the abundance of fish stocks and their yields have been studied intensely for the last century. It is generally accepted that man's impact through harvesting has introduced an additional element into the already complex dynamics characterizing individual stocks. In addition, there is speculation that man has also affected these stocks through nonfishing activities that produce pollutants, alter habitats, and add nutrients to estuarine water bodies. Opinions differ concerning the relative importance of these anthropogenic factors vs natural environmental factors.

Overfishing has been suggested as an important factor in some of these declines of stocks (Rothschild et al., 1981), but other evidence suggests that pollution and man-made alterations to natural habitats also may have contributed. Resource managers, scientists, and the interested public have expressed deep concern about the future of these resources. This concern stems from documented declines in harvest levels for many stocks (e.g., Esser, 1982), reports of increasing waste loads in estuarine basins (e.g., Gunnerson et al., 1982; Mytelka et al., 1982), and observed alterations in many natural-habitat features (e.g., Peters, 1982; Stevenson, 1898).

Common sense dictates that these obvious changes, alone or in combination, are detrimental to some stocks, and might ultimately threaten even the persistence of some stocks. Unfortunately, it is difficult to establish from the available information whether stock abundances have undergone systematic declines, and it is even more difficult to advance testable cause-and-effect relationships that could indicate the specific natural and man-induced factors governing population variability. In fact, the evidence concerning the historical status of both stocks and pollution levels is largely qualitative and anecdotal. Neither exploitation nor pollution effects -- the two major classes of potentially detrimental factors affecting stocks -- can be unequivocally blamed for the deterioration of estuarine fisheries in general (Bell and Pruter, 1958; McHugh, 1977).

Natural fluctuations in stock abundance have been related to natural environmental variables (e.g., freshwater discharge, temperature, and salinity). Landings of anadromous stocks such as striped bass (*Morone saxatilis*), American shad (*Alosa sapidissima*), and alewife (*Alosa pseudoharengus*) have been statistically related to freshwater discharge (Stevens, 1977; Talbot, 1954; Tiller, 1950), temperature (Dow, 1977; Merriman, 1941; Sutcliffe et al., 1977), or some combination of environmental variables (Schaefer, 1968). Variations in estuarine stock abundance, as determined by landings of white perch (*Morone americana*), have been strongly related statistically to variations in salinity and temperature (Summers et al., 1982). Estuarine and inshore shellfisheries such as those of American lobster (Homerus americana), American oyster (Crassostrea virginica), brown shrimp (Penaeus azterus), soft clam (Mya arenaria), and hard clam (Mercenaria mercenaria) appear to be affected by temperature, salinity, freshwater discharge, upwelling, or some combination of these variables (Botsford and Wickham, 1975; Dow, 1964, 1969, 1977; Flowers and Saila, 1972; Gunter and Edwards, 1967; Hunt et al., 1979; Pearson, 1948; Sutcliffe, 1972, 1973, 1977; Ulanowicz et al., 1982). Temperature was traced as an indirect cause of stock size variation in soft clams in the Gulf of Maine by its direct affect on the green crab (Cancer maenus), a major predator on soft clams (Welch, 1968; McHugh, 1977). Stock size of menhaden (Brevoortia tyrannus), an oceanic spawner that uses estuarine regions as a nursery habitat, may be affected by wind-induced currents (Nelson et al., 1977). The success of other oceanic stocks (i.e., those of cod, Gadus morhua; Atlantic sea herring, Clupea harengus; silver hake, Merluccius bilinearis; yellowtail flounder, Limanda ferruginea; Atlantic mackerel, Scomber scombrus; lemon sole, Parophrys vetulus; haddock, Melanogrammus aeglefinus; and yellowfin tuna, Thunnus albacares) has been related to temperature, salinity, upwelling, and wind-driven currents (Blackburn, 1969; Carruthers, 1951; Chase, 1955; Craig, 1960; Dickson, 1971; Dickson et al., 1973; Dow, 1977; Hayes et al., 1977; Hermann et al., 1965; Hill and Lee, 1957; Ketchen, 1956; Lett and Kohler, 1976; Martin and Kohler, 1967; Sutcliffe et al., 1977; Templeman and Fleming, 1953). Sunspot activity has even been suggested to affect stock success indirectly by controlling environmental trends (Favorite and Ingraham, 1976; Southward et al., 1975).

The effect of human activities (e.g., fishing, industrial pollution, dam construction, and sewage generation) on stock abundance has been discussed since before the turn of the century. Overfishing is often blamed for the major declines in important food fisheries in the late 1800's [Dennis, 1910; d'Homergue, 1883; Goode, 1887; Hathaway, 1910; Reports to U.S. Fish Commission (1882-1901); Spangler, 1894] as well as for those in later years (Rothschild et al., 1981). Other evidence suggests that stock abundance can be reduced by pollution (industrial, municipal, and/or agricultural) and man-made changes in natural habitats (dams, dredging) (Burdick, 1954; Carriker et al., 1982; Commission of Fisheries of New Jersey, 1885; McHugh and Ginter, 1978; Sindermann et al., 1982; Mearns et al., 1982; Stevenson, 1898; Talbot, 1954; Wolfe et al., 1982). Studies have also suggested that pollution can indirectly increase some stocks (Tsai, 1984), that increased populations of blue-green algae (often associated with nutrient loadings) can accelerate the growth rate of juvenile herrings (S. Mozley, North Carolina State University, pers. comm.), and that efforts to clean up polluted regions can decrease stock size population (D. Rhoads, Yale University, pers. comm.). Most of the relationships between pollutant inputs and stock abundances are conjectural.

It cannot be denied that stocks fluctuate greatly. The specific causes of the fluctuations are not known, but certainly environment and possibly human activities strongly affect population dynamics. Determining the means by which natural environmental factors and anthropogenic factors act -- separately as well as jointly -- in regulating stock abundance is a prerequisite for a realistic approach to the maintenance of fisheries and the management of aquatic pollution.

1.2 Historical Fisheries/Pollution Program

In 1982, under a grant from the NOAA Ocean Assessments Division (OAD), Martin Marietta Environmental Systems embarked on a study of the effects of pollution on estuarine fish stocks, with particular emphasis on changes observed in the Hudson-Raritan basin. The major purpose of the study was to develop and evaluate hypotheses, based on historical records, that link population-level responses of fish and shellfish stocks to pollution stresses. The primary approach was to examine the relationships between stock abundance in five northeastern estuaries and all potentially important causal factors (e.g., climate, pollution, man-made alterations in habitat). Although the study focused on the Hudson-Raritan estuary, four additional relatively stressed and relatively unstressed estuaries were studied for comparison.

The 2-year program was a joint effort of Martin Marietta Environmental Systems (Martin Marietta) and Carnegie-Mellon University (CMU). The individual responsibilities of the two organizations are listed below:

- Martin Marietta -- Collect all appropriate data on landings, fishing effort, climate, freshwater discharge, and water quality for the target estuaries
- CMU -- Conduct all historical research on industrialization, land use patterns, and municipal and pollutant loading
- Martin Marietta -- Synthesize the pollution data into readily usable time-series to indicate pollution trends
- Martin Marietta -- Incorporate all data into a general database
- Martin Marietta -- Develop quantitative techniques for the study of important factors affecting stock variability, with emphasis on pollutants
- CMU -- Review the pollution histories of individual target estuaries to identify pollution and pollutant-loading trends
- Martin Marietta -- Evaluate and interpret the results of all analyses in both ecological and managerial contexts
- Martin Marietta -- Develop rigorous hypotheses relating stock abundance of commercial fisheries and shellfisheries to pollution.

This report describes the activities of the Historical Fisheries/Pollution Program, including the collection of data, the development of a computerized database, and the performance of all analyses. Data transferred from Carnegie-Mellon to Martin Marietta Environmental Systems are referred to as the pollution input database. Additional information on methods for collecting pollutant history data can be found in Tarr and McCurley (1984).

The objective of this Historical Fisheries/Pollution Program is to determine whether there is historical evidence for significant relationships between estuarine stock declines and pollution in northeastern estuaries. In accomplishing this goal, we must formulate rigorous hypotheses that could be tested experimentally for specific species.

Many investigators and fisheries managers have accepted pollution as a major cause for stock declines despite the lack of specific, concrete evidence. Analyses are necessary to remove the assessment of pollution effects on commercial fish from the realm of allegation and provide support or contradiction for the above hypothesis. Two types of analyses could be performed:

- Actual experimentation on all target fisheries and all candidate pollutants
- Determination of apparent pollution effects from existing data.

There are difficulties with both approaches. Given limited funding, the first approach is impossible because of the high cost of bioassay experiments. The second approach suffers in that the needed historical data may not exist, and even if they do, applicable analytical methods may not have been established. Even so, if appropriate data and methods can be found, the historical approach will produce a subset of the total possible bioassays. This subset will provide a reasonable set of conditions on which to base experimental hypothesis testing. The primary purpose of the historical approach is to develop a manageable set of stock-pollution combinations that will permit direct testing of cause-and-effect relationships (i.e., to generate rigorously testable hypotheses).

The dissolution of stock history for any fishery into components that can account for its temporal variation is not a trivial task. Ideally, we would initiate the analytical process from a true measure of abundance for the population over time (i.e., 1929 to present). No such measure exists, but catch-per-unit-effort is an acceptable relative estimate of stock abundance. This estimate uses the ratio of landings for a particular stock, and the fishing effort associated with those landings (e.g., number of square yards of gill net), to approximate the relative abundance of fishable stock (i.e., those members of the population that can be caught). It is this measure of relative stock history that can be examined historically to evaluate the potential effects of climate and pollution on stock success.

In many fisheries, stock success is determined by abundance of juveniles. Thus, the environmental events (whether hydrographic or anthropogenic) that most affect the stock are those that affect its early life stage mortality. For example, poor water quality, below-normal temperatures, and low food supplies could all contribute to the production of a poor juvenile population or year-class. Thus, these variables affect the fishable stock at time x by their action some number of years previously (x-i, where i represents the number of years from hatching to recruitment into the fishery). While this example is somewhat simplistic in that often several different lags (x-i) are involved, the concept of lagged effects of hydrographic and pollution variables on stock abundance is basic to our approach.

Stock history can be partitioned in a stepwise manner to progressively remove the part of its variation that can be explained by selected variables (Fig. 1). First, a lagged stock component of stock abundance (a component based on the life history characteristics of the individual stock) can be removed to account for cyclicity in the stock and possibly for some residual fishing-pressure effects. Climatic variation in year-class success would next be removed to account for variation in stock size due to annual variation in climatic conditions (e.g., temperature, freshwater discharge, wind). Thus, all

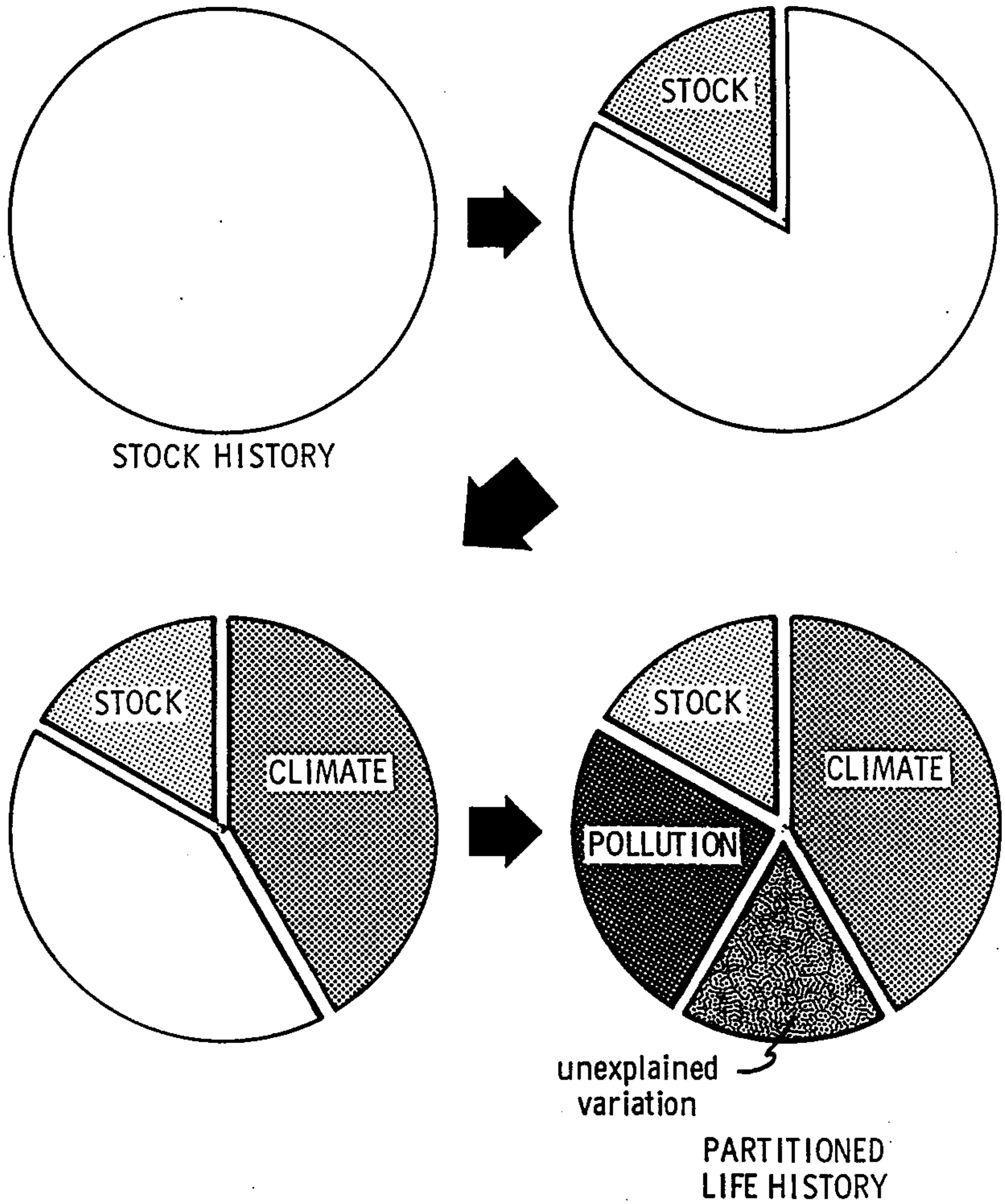


Figure 1. Conceptual rationale for analyses in the Historical Fisheries/ Pollution Program.

natural variation in stock abundance (stock and climate components) is accounted for before we investigate the potential relationships between stock and pollution variates. Clearly, other phenomena, which are not explicitly tested, could also affect stock size; and their effects (i.e., unexplained variation) will remain after the removal of potential pollution effects.

A statistical association of this type does not imply causality. Rather, these analyses permit the construction of rigorously testable hypotheses about potential cause-effect relationships for each target fishery.

Before the start of the program, representatives from the NOAA/Office of Marine Pollution Assessment (now NOAA-OAD), Martin Marietta Environmental Systems, Carnegie-Mellon University, and Battelle Northeast Laboratories met to decide two questions about the design of the study, namely:

- Which estuaries would be the focus of investigation?
- Which fisheries in each estuary would be studied?

Table 1 lists the estuaries chosen for investigation and describes their gross physical and biological characteristics. The choice was based primarily on environmental/ecological similarity to the principal target estuary, Hudson-Raritan system, and on the adequacy of exploitation records for the region. In addition, these estuaries were chosen to bracket the Hudson-Raritan estuary in climate, since climatic trends along the northeastern coast may affect stock abundance.

The Potomac River was selected to represent a "relatively unpolluted" estuary with large runs of anadromous fishes (e.g., striped bass and shad), and also to represent a part of the Chesapeake Bay system that is manageable with respect to acquisition of data on fisheries, environmental parameters, and pollution. The Delaware River/Bay, the Hudson River-Raritan Bay estuary, and the Narragansett Bay were chosen to represent "polluted" estuaries with large commercial fisheries. The Connecticut River was chosen as a "relatively unpolluted" river, although it clearly is affected by other anthropogenic factors (i.e., dams). Individual differences in these target estuaries were expected to cause problems in the comparison. For example, the Narragansett Bay system is physically very different from the other four estuaries (i.e., a well-mixed polyhaline estuary vs oligohaline-mesohaline systems), and the Connecticut River has only a few extensive commercial fisheries (for shad and blue crabs).

Table 1. Target estuaries for the Historical Fisheries/Pollution Program

Estuary	Characteristics: Physical	Characteristics: Biological
Hudson River-Raritan Bay	Fresh to polyhaline Polluted	Numerous commercial fisheries (anadromous, estuarine, and oceanic stocks)
Delaware River/Bay	Fresh to polyhaline Polluted	Numerous commercial fisheries and shellfisheries (anadromous, estuarine, and oceanic stocks)
Potomac River	Fresh to mesohaline/polyhaline Relatively unpolluted	Numerous fisheries and shellfisheries (anadromous and estuarine stocks)
Narragansett Bay	Polyhaline Polluted but well flushed	Numerous shellfisheries and fisheries (oceanic stocks), if Rhode Island Sound is included
Connecticut River	Fresh to mesohaline Relatively unpolluted Large number of dams	Few commercial species other than shad

2. POLLUTION DATA

2.1 Measures of Pollution

Ideally, historical time series of human-induced habitat alterations and of specific pollutant loadings into various spatial segments of an estuary would be constructed from historical records. Until recently, however, quantitative data on most pollutants and habitat alterations were not recorded consistently, and most historical references containing quantitative data are fragmentary and anecdotal. Historical time series of specific pollutant loadings and habitat alterations can, therefore, only be estimated by use of indirect methods. Since estimation is a difficult and time-consuming task, Martin Marietta Environmental Systems and Carnegie-Mellon University defined two types of pollution variables -- macropollution variables and micropollution variables -- based on the relative ease with which adequate time series could be constructed from each type of variable.

Macropollution variables ("macrovariables") are aggregate variables indirectly representing general trends in human-related activities, habitat changes, and pollution in the estuarine watersheds, such as demographic patterns in the watersheds and trends in water quality parameters. Micropollution variables ("microvariables") are the direct measures of the loadings of specific pollutants (e.g., cadmium, lead) into the estuaries, which can be associated, spatially and temporally, with a particular river segment. Data on macrovariables are directly available from historical records, but data on microvariables may not be; thus historical time series can be constructed more easily for macrovariables than for microvariables. Results of analyses on macropollution variables are, however, necessarily only preliminary, because the macropollution data lack specificity.

In this report, relationships between pollution trends and estuarine fisheries are assessed from consideration of macrovariables only. The specific macropollution time series used in the analyses described in Section 4 are detailed below. Micropollution time series were estimated by Variflex, Inc. (Ayers et al., 1985; Ayers and Rod, 1986).

2.2 Collection of Macropollution Data and Description of Database

Carnegie-Mellon University was responsible for conducting the historical research on the pollution trends in each estuary and transmitting to Martin Marietta Environmental Systems the data suitable for time-series construction. Details of the methods used and the types of data collected, and descriptions of the pollution history of each estuary, can be found in Carnegie-Mellon's companion report (Tarr and McCurley, 1984). The Carnegie-Mellon data were entered into the Martin Marietta Environmental Systems/NOAA database in files formatted in SAS (Statistical Analysis System).

2.3 Construction of Time Series

The construction of any time series from historical data requires that the data have been collected in a consistent manner, at regular intervals that are short enough to reveal trends, and for long enough to span the period of interest. The major constraints imposed by this program were that the macropollution time series must span at least the period covered by the landings data for the target fisheries in each estuary (see Section 3), and the variables must reflect trends in human activities in the estuarine basins. Macropollution time series were constructed for each estuary, either directly from the Carnegie-Mellon data or from information provided by Carnegie-Mellon and augmented by Martin Marietta.

In general, data on six macropollution variables were sufficient to allow construction of adequate time series. These variables reflected monotonic trends in human population, employment levels, and agricultural land use in counties surrounding the estuaries; i.e., short-term and annual variation of dredging activity, dissolved oxygen, and municipal sewage loadings in the target estuarine watersheds. For some estuaries, data on some of these variables were lacking, so macropollution time series could not be constructed for these macrovariables in every estuary. Information on each macrovariable, including the source(s) of the data used in constructing time series and the details of the time-series construction that were specific to each estuary, are presented below.

- Human Population -- Figures 2 to 6 show the trends in human population in each of the five estuarine basins. The data were obtained from the U.S. Decennial Census of Population and consisted of the human population in counties bordering the regions of each estuary that generally support estuarine fish stocks.

- Agricultural Land Use -- Figures 7 to 11 show the acreage in improved farmland in each of the estuarine watersheds. Farmland data on a county basis were obtained from the U.S. Agriculture Census, and similar counties chosen for use in the work with human population macrovariables were also used in the work with improved farmland.

- Employment Levels -- A time series of the total number of employees in manufacturing industries was constructed for counties bordering the lower Potomac River (Fig. 12) from the U.S. Census of Manufacturing. Changes in the census methods of collecting and classifying employment data caused substantial difficulties in the standardization of the data, a requirement for constructing a consistent time series. Since the trends in number of employees closely mimicked the trends in human population, time series of the number of employees in manufacturing were not constructed for the other estuaries.

- Dredging Activity -- The total volume dredged annually by river mile for each estuary was extracted from annual reports of the U.S. Army Corps of Engineers. For the Hudson/Raritan and Delaware estuaries, spatial segments to be studied were defined to correspond to the general spawning areas of the various types of fishes included in the analyses. For the Hudson/Raritan, volume dredged was totalled as follows: for anadromous species, miles 40-165 of the Hudson proper (Fig. 13); and for the other species, miles 0-165 of the Hudson proper, 0-15 of the Raritan Bay and Arthur Kill, and all of the Harlem River (Fig. 14). For the Delaware estuary, volume dredged was totalled for river miles 90-135 for anadromous species, 0-90 for species that use the estuary as nursery grounds, and 0-135 for the remaining species (Figs. 15 to 17). Figures 18 to 20 show the total volume dredged for

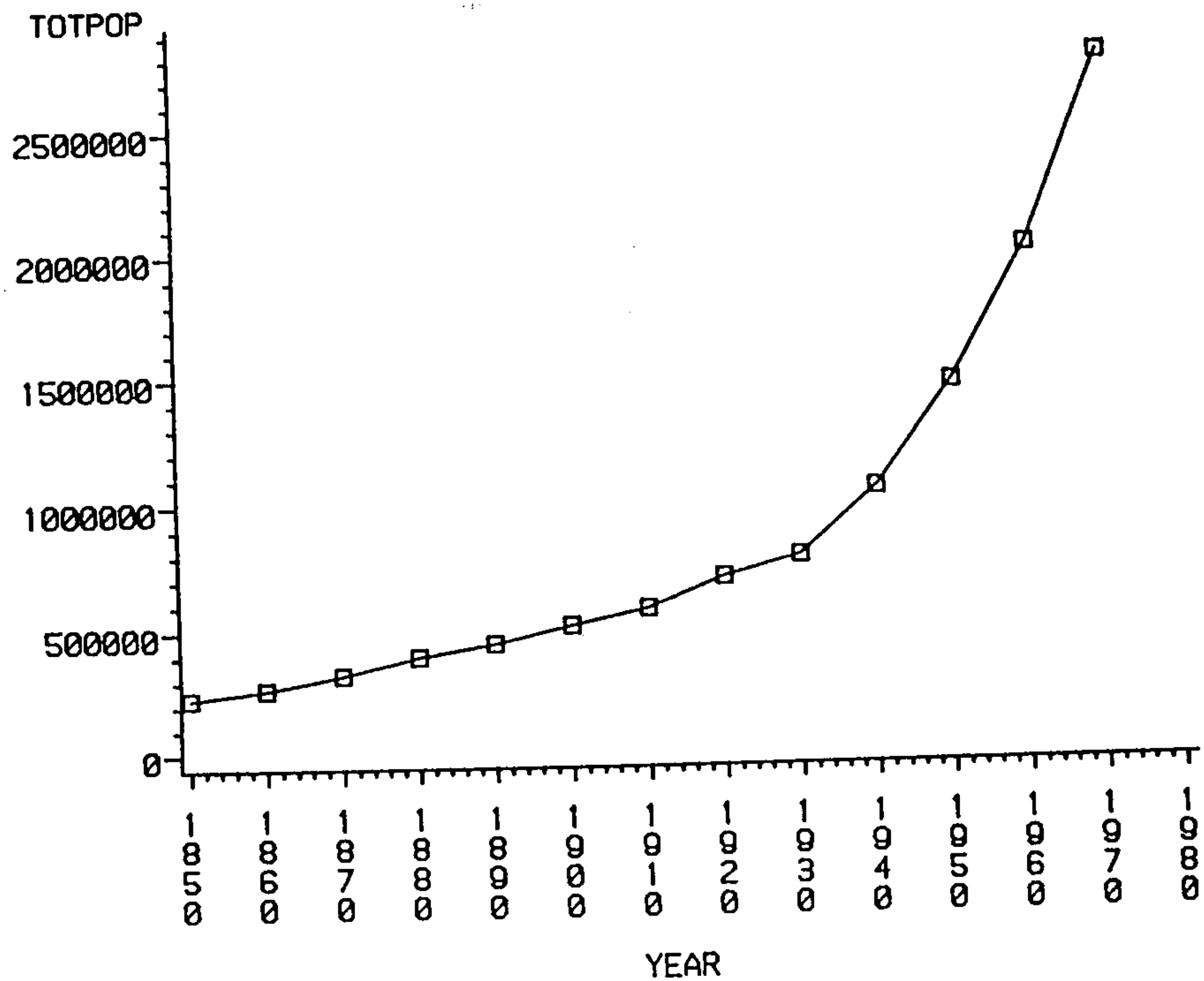


Figure 2. Human population in counties bordering the portion of the Potomac River that generally supports estuarine fish stocks.

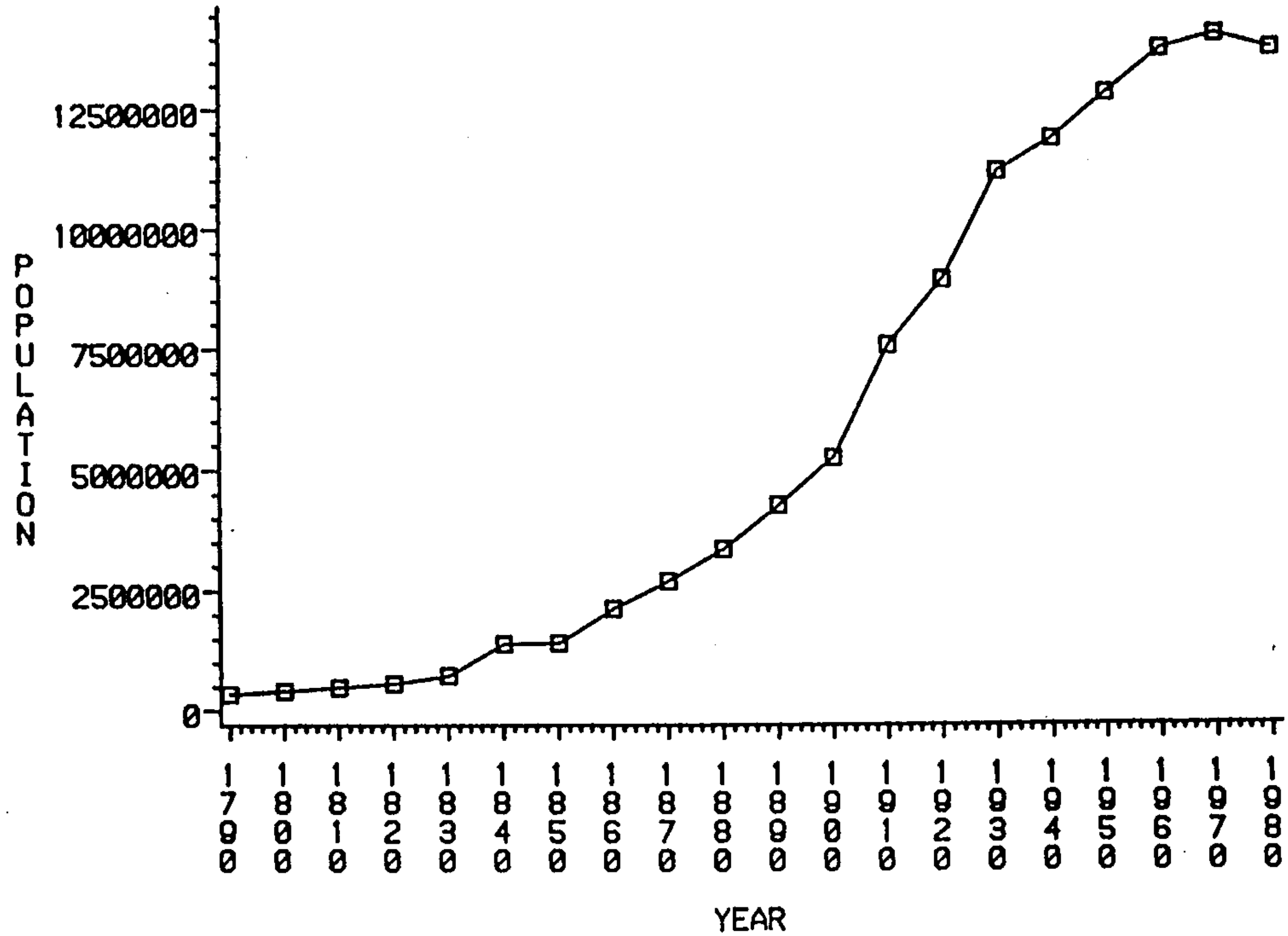


Figure 3. Human population in counties surrounding the portion of the Hudson-Raritan estuary that generally supports estuarine fish stocks.

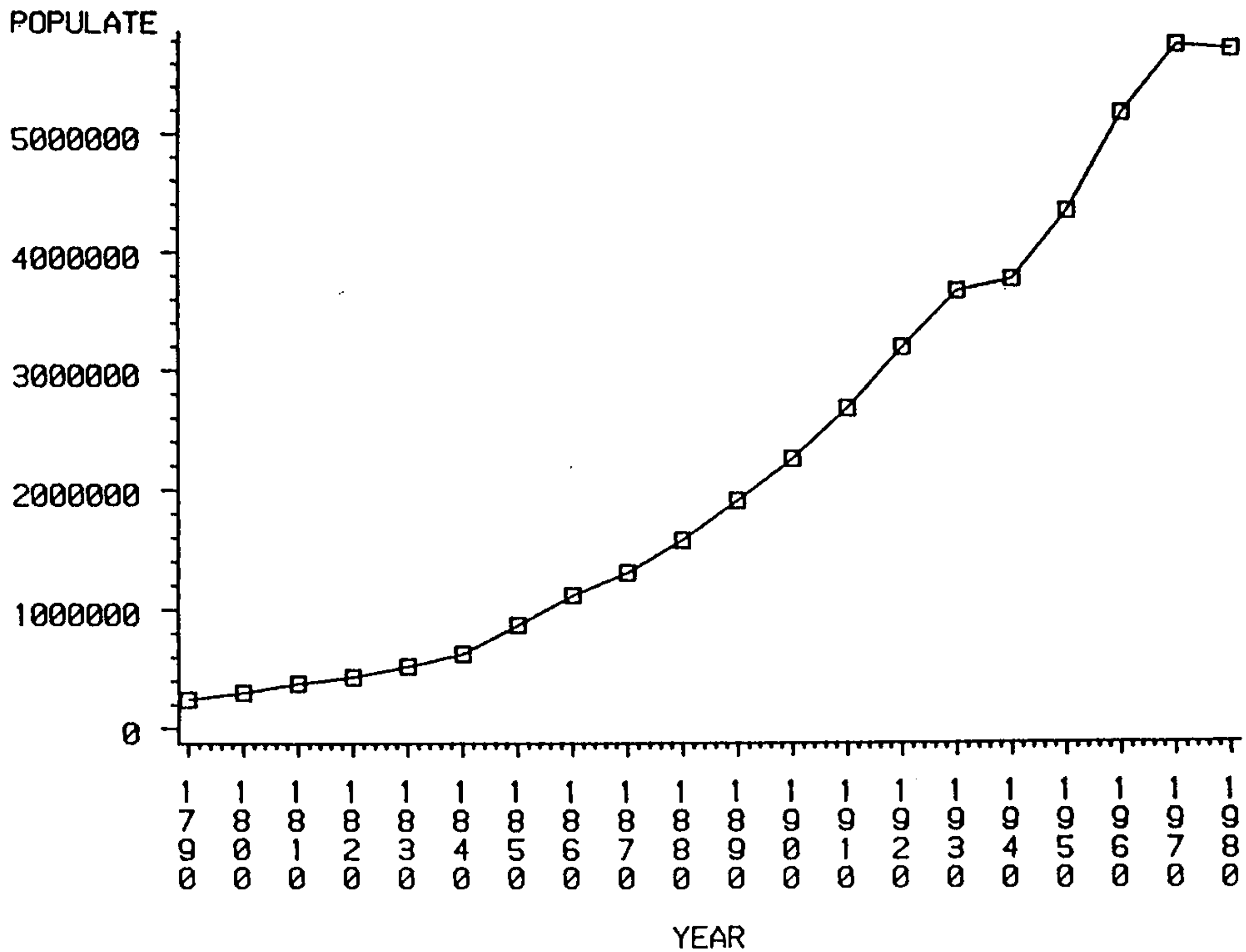


Figure 4. Human population in counties surrounding the portion of the Delaware River that generally supports estuarine fish stocks.

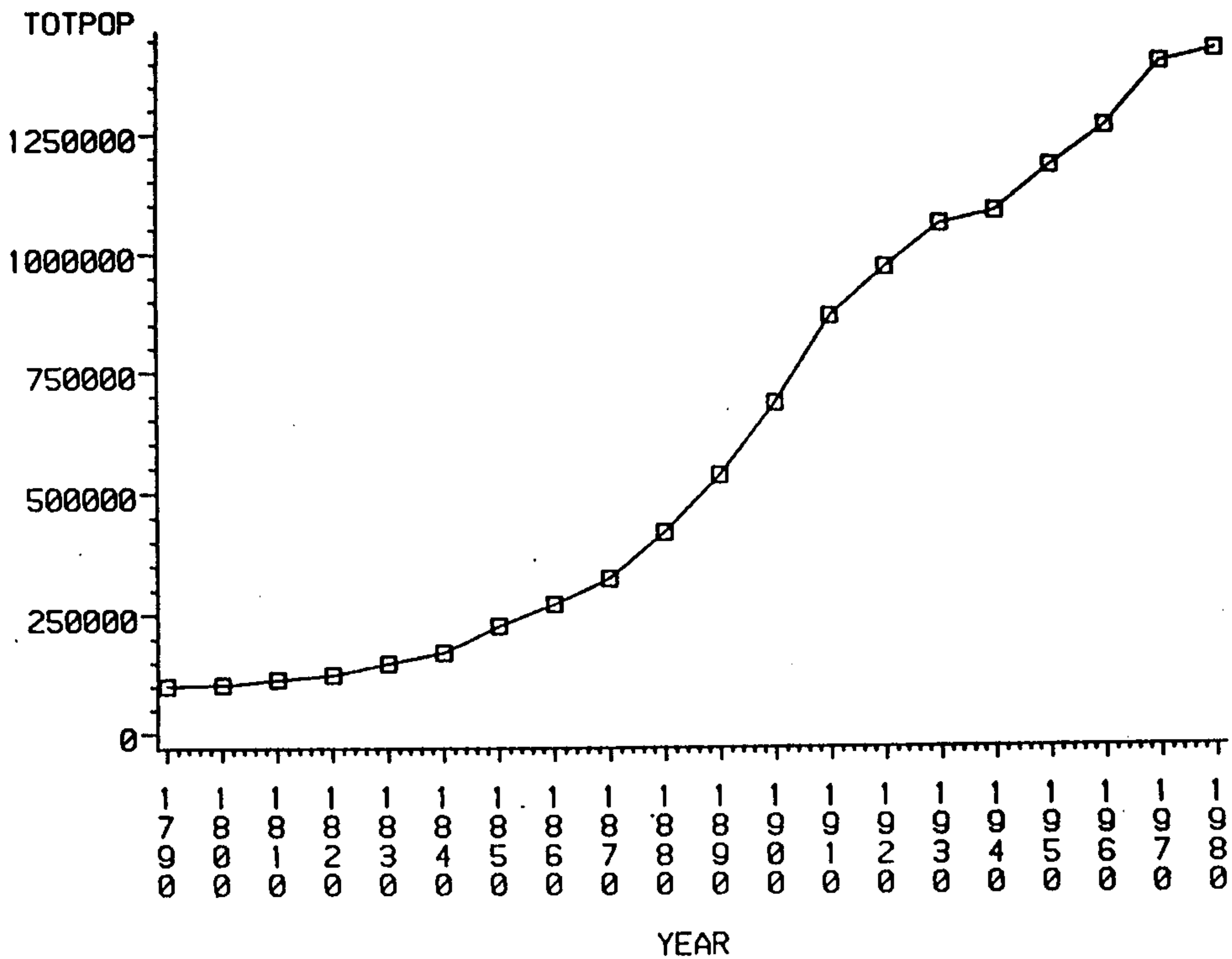


Figure 5. Human population in counties bordering the Narragansett Bay.

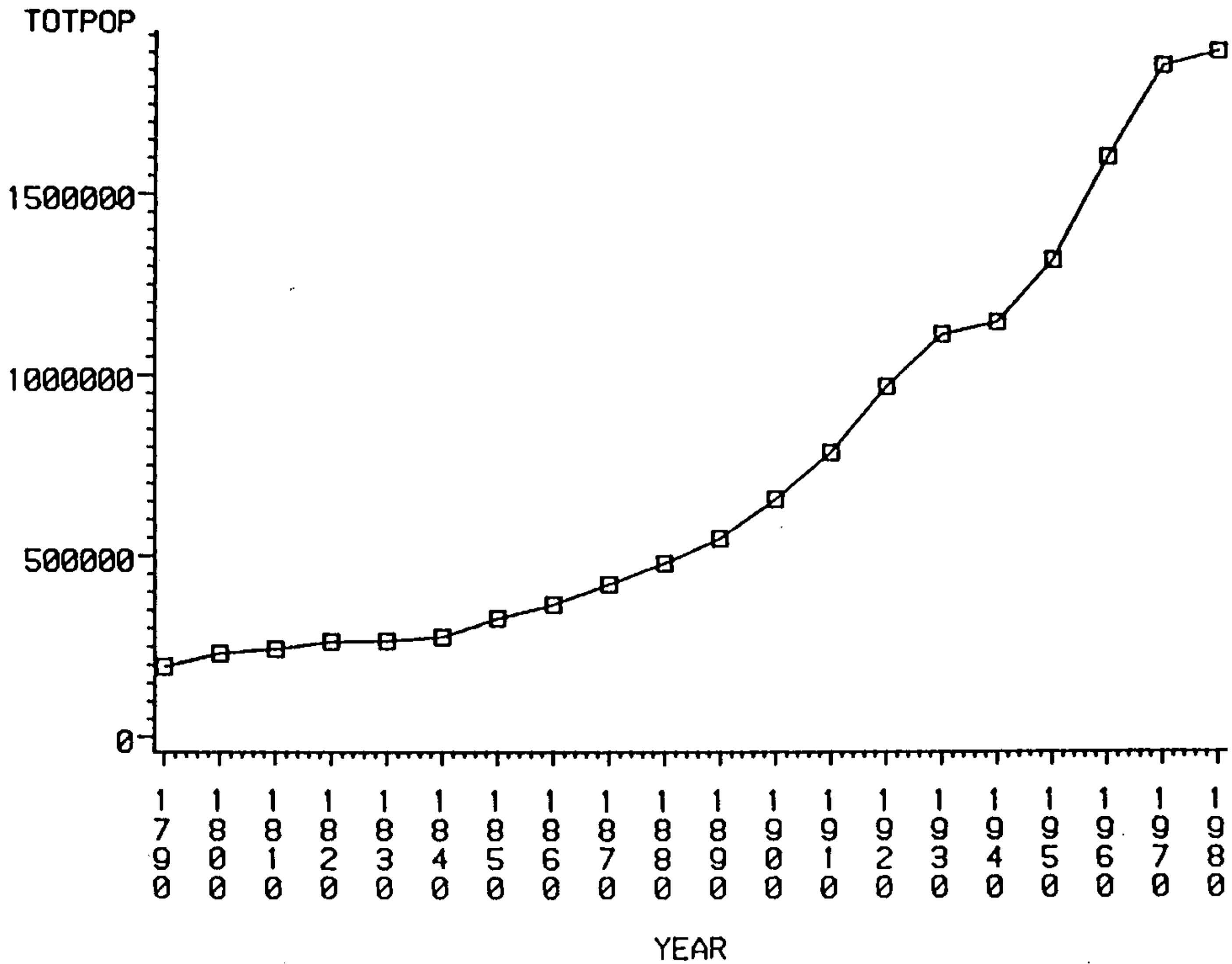


Figure 6. Human population in counties bordering the portion of the Connecticut River that generally supports estuarine fish stocks.

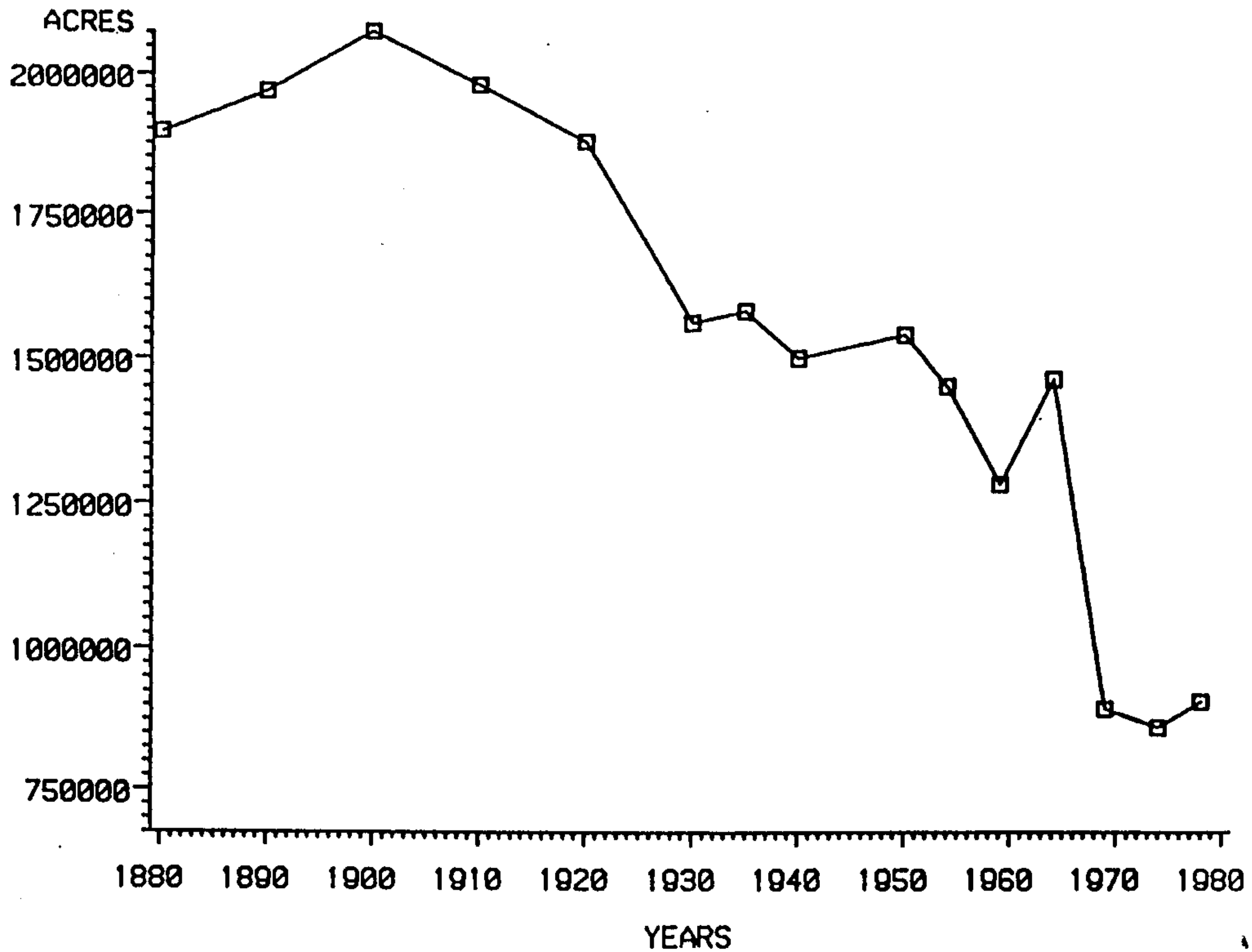


Figure 7. Acreage in improved farmland in counties bordering the portion of the Potomac River that generally supports estuarine fish stocks.

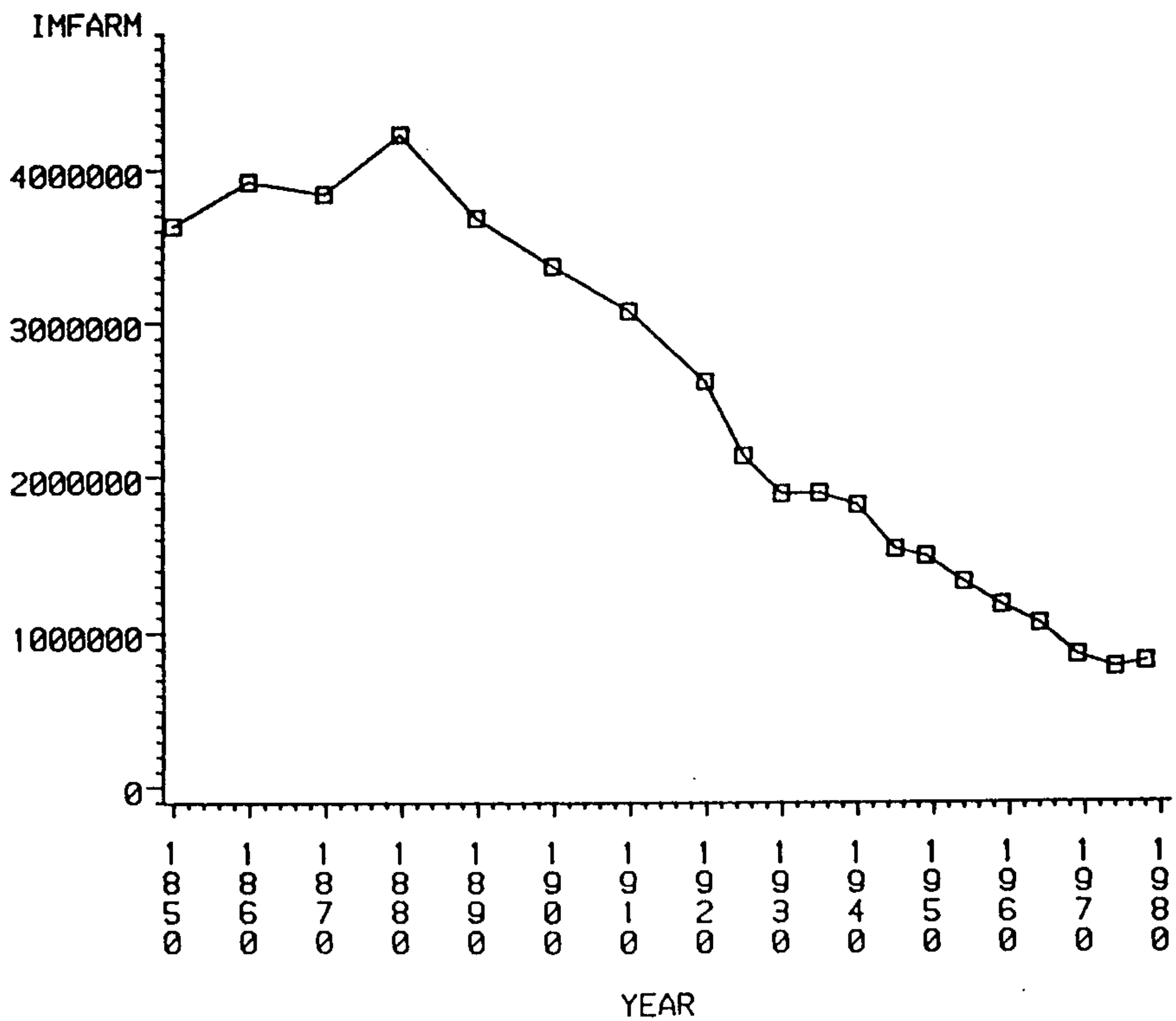


Figure 8. Acres in improved farmland in counties bordering the portion of the Hudson/Raritan estuary that supports estuarine fish stocks.

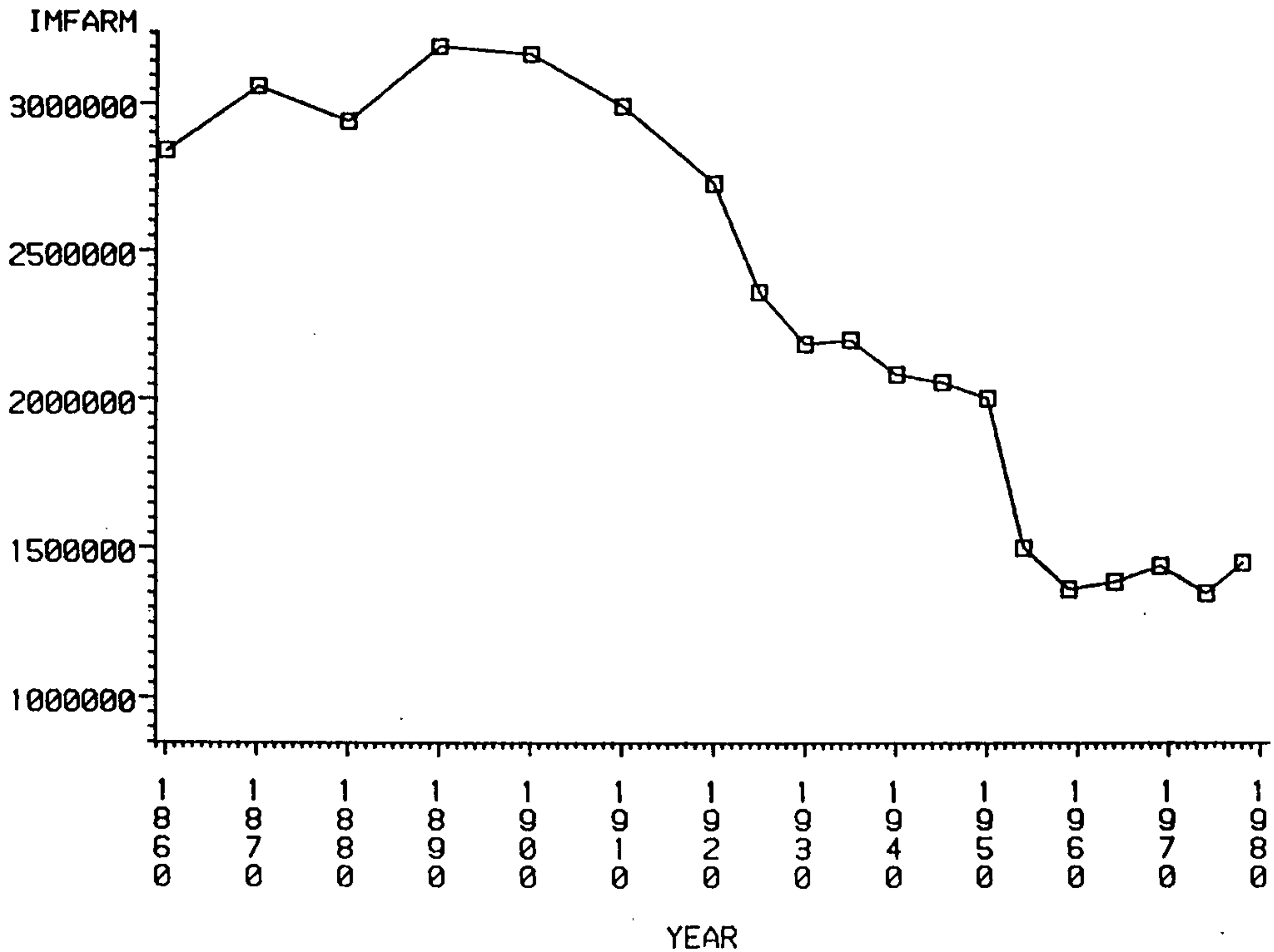


Figure 9. Acres in improved farmland in counties bordering the portion of the Delaware River that supports estuarine fish stocks.

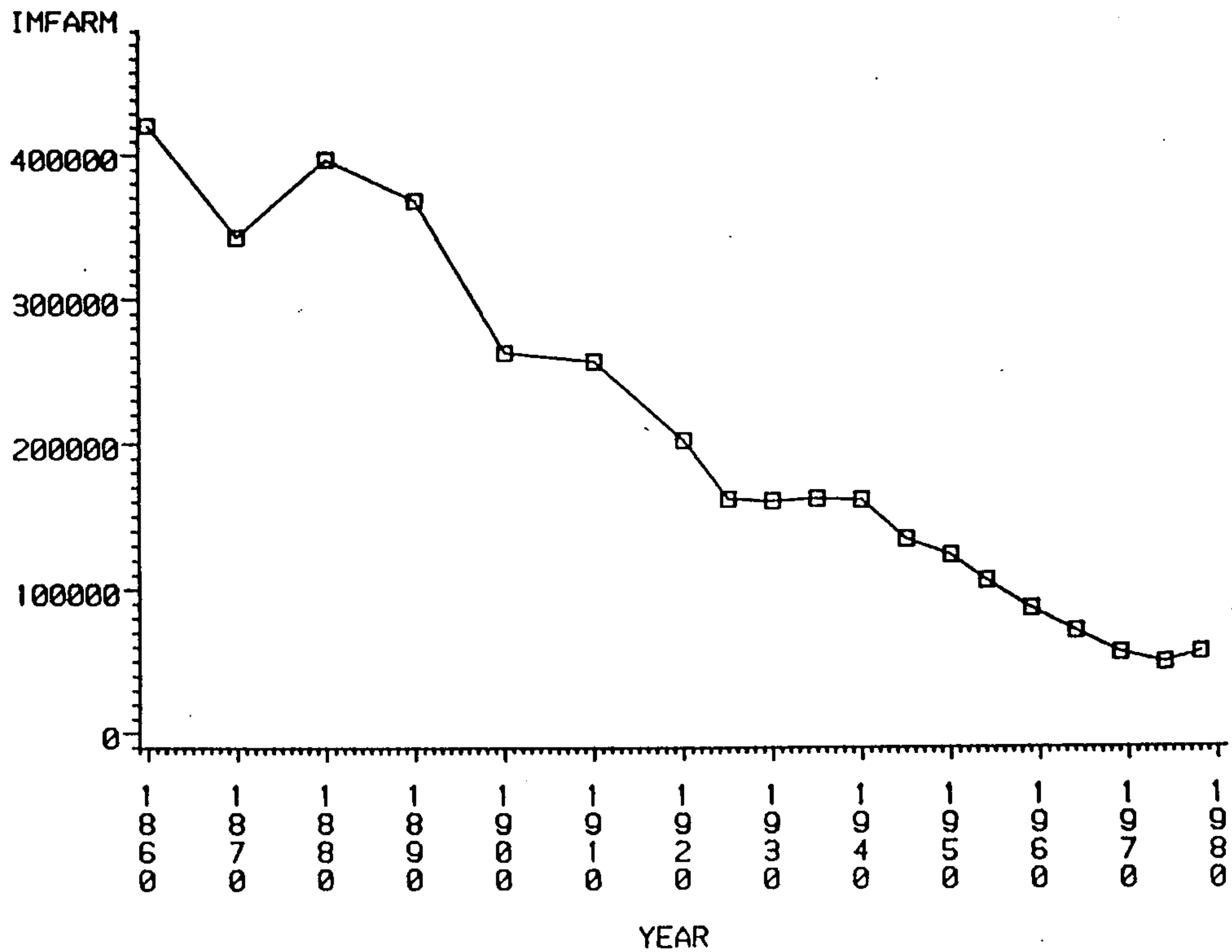


Figure 10. Acres in improved farmland in counties bordering the Narragansett Bay.

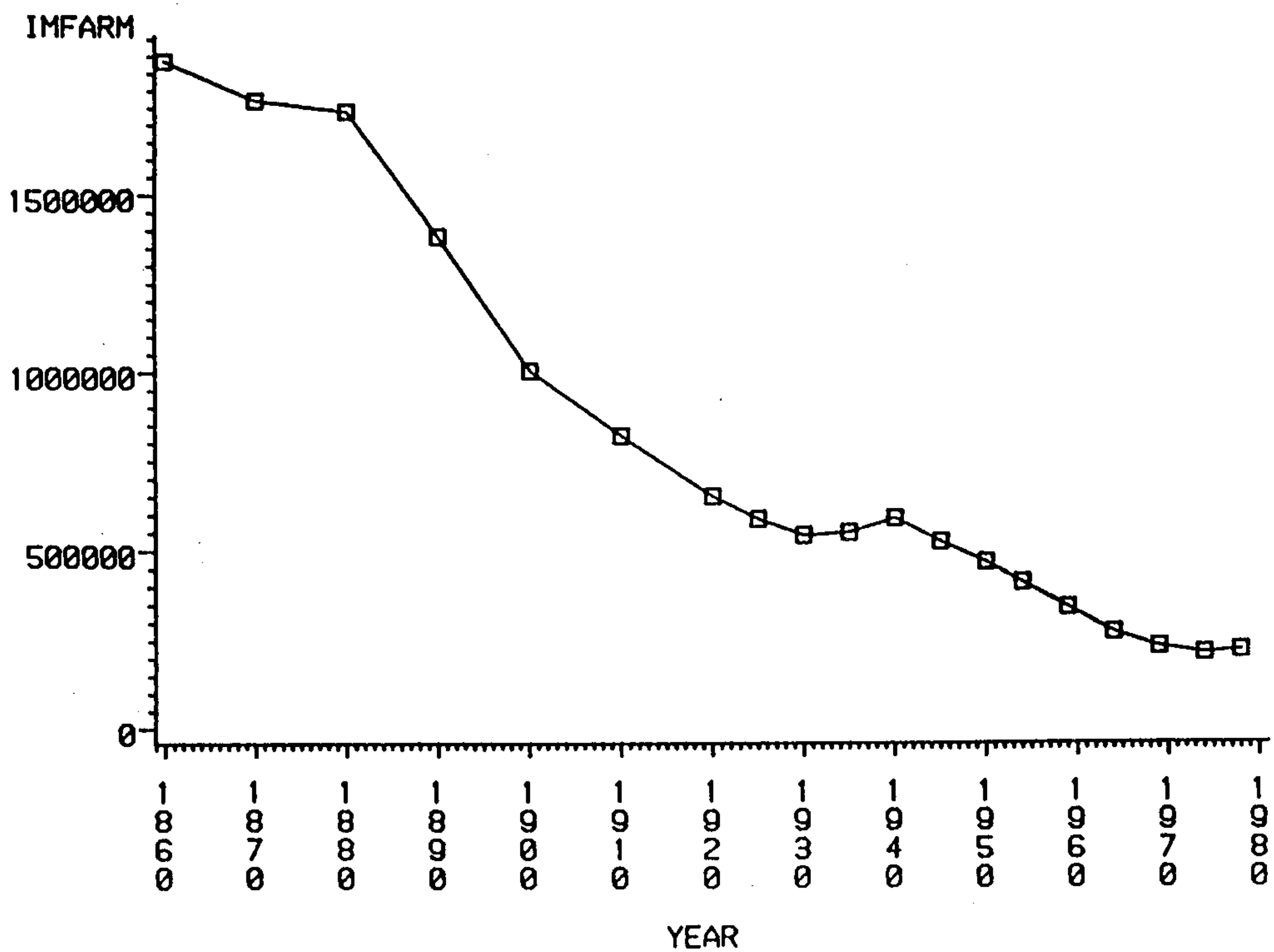


Figure 11. Acres in improved farmland in counties bordering the portion of the Connecticut River that supports estuarine fish stocks.

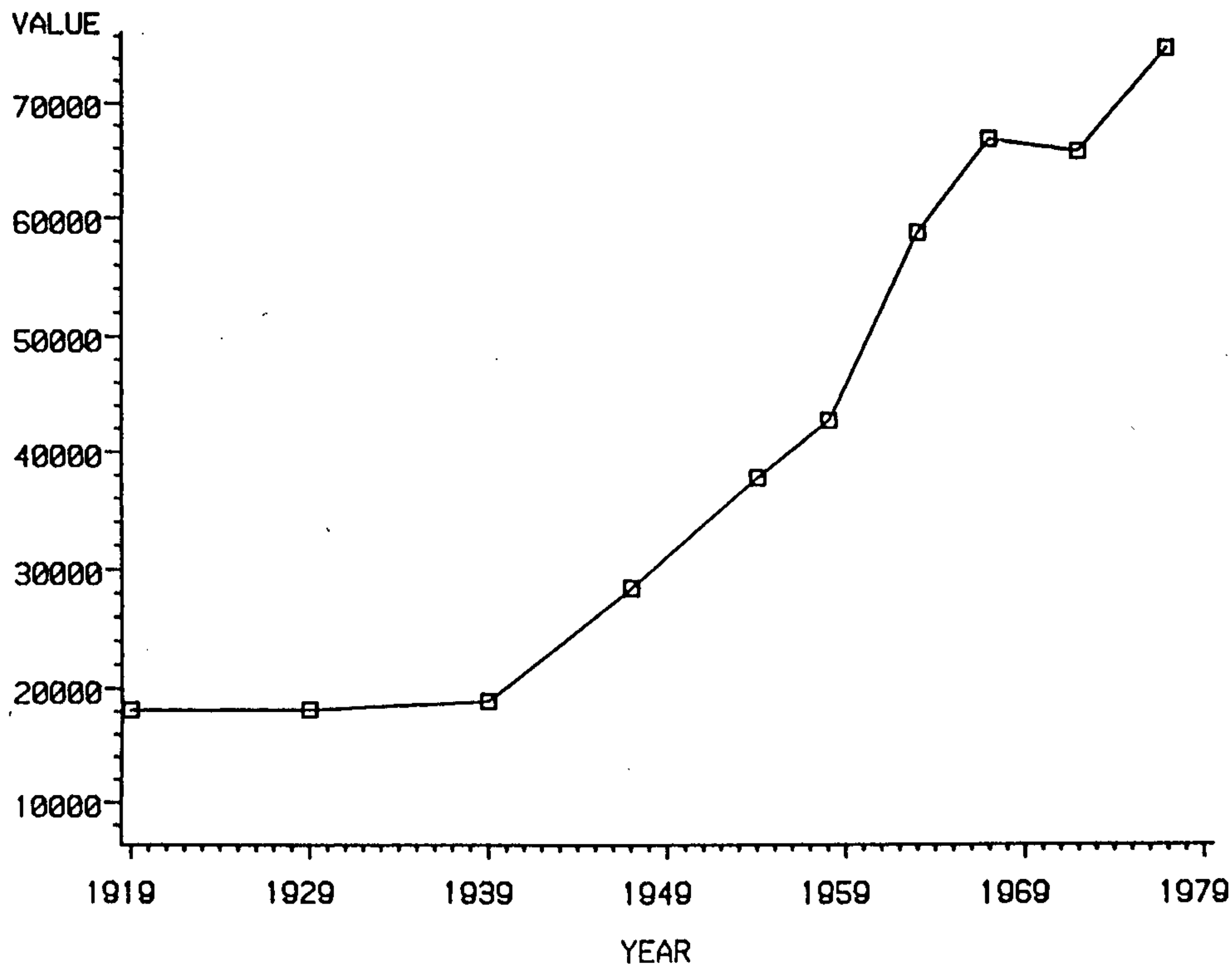


Figure 12. Total number of employees in manufacturing industries in counties bordering the lower Potomac River.

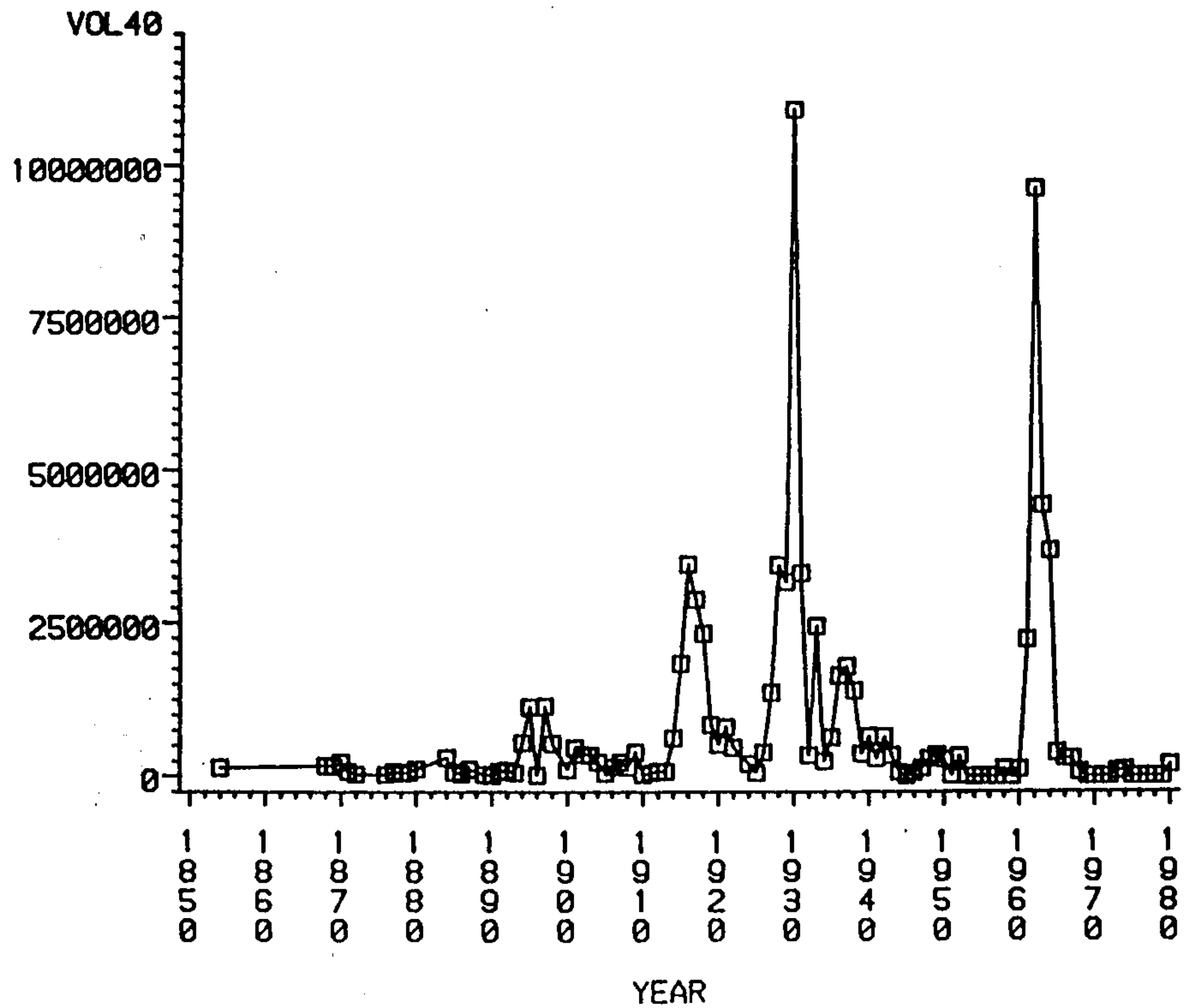


Figure 13. Total volume of material dredged from miles 40-165 in the Hudson River.

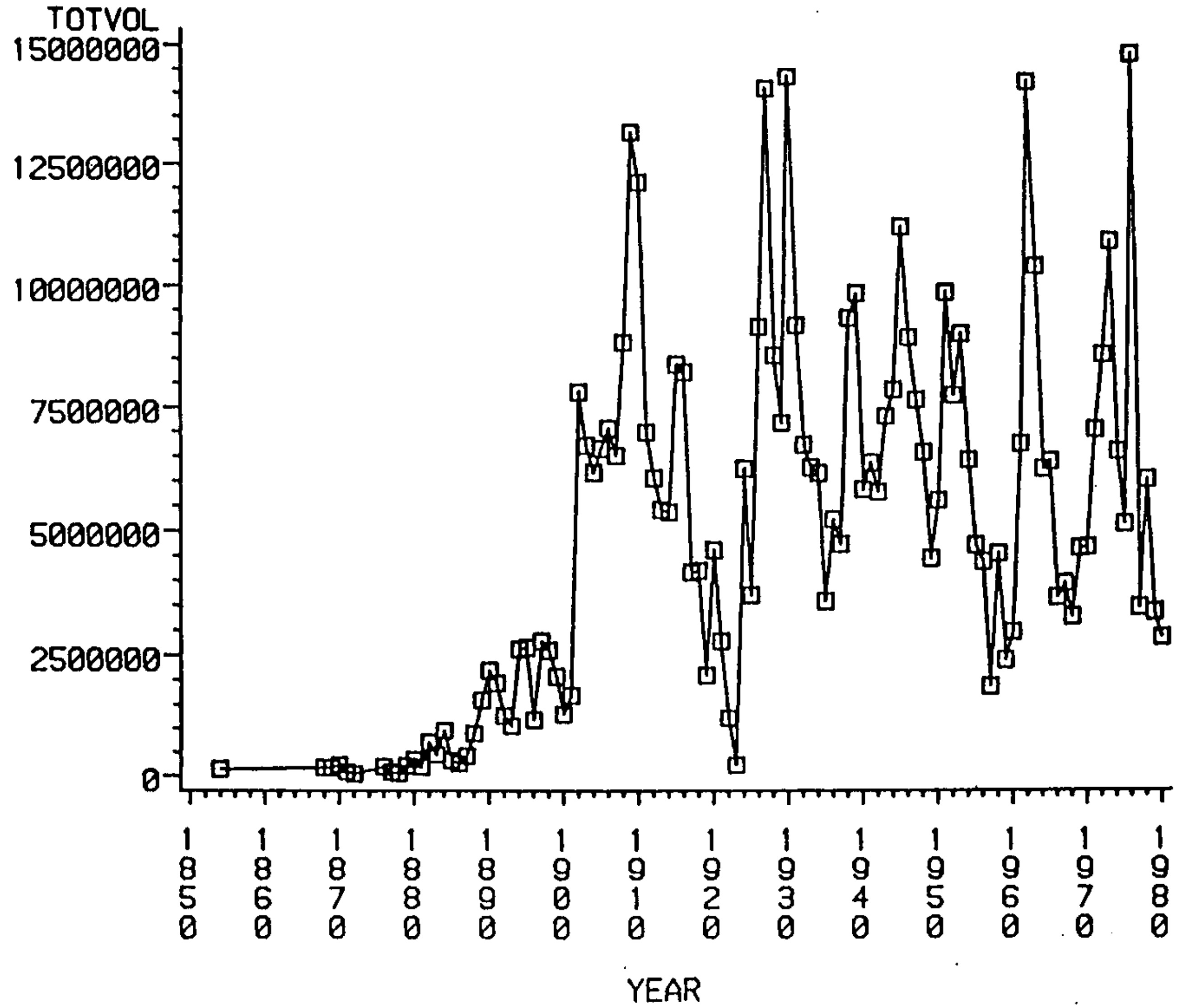


Figure 14. Total volume of material dredged from miles 0-165 in the Hudson River, miles 0-15 in the Raritan River/Bay and Arthur Kill, and the entire Harlem River.

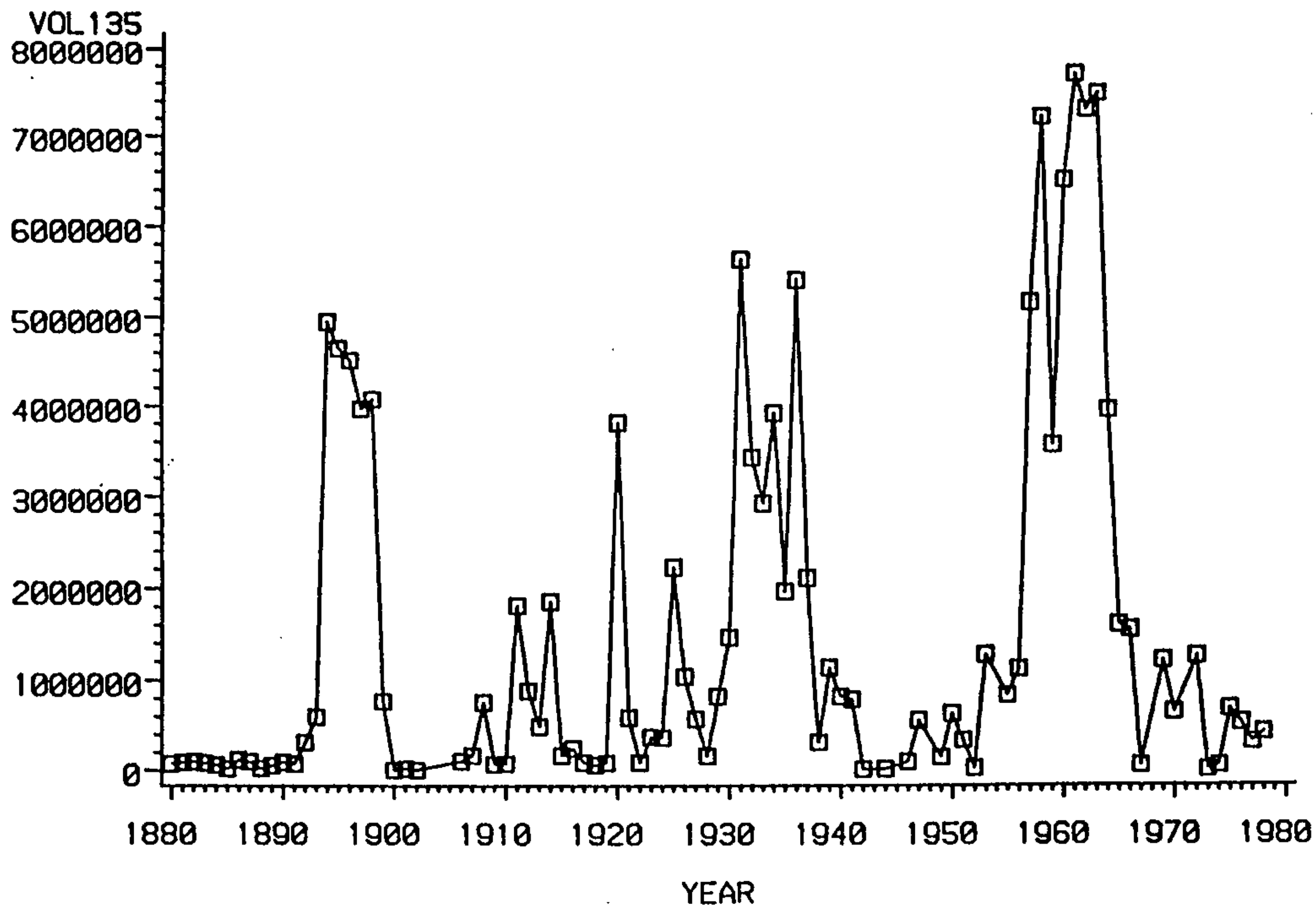


Figure 15. Total volume of material dredged from miles 90-135 in the Delaware River.

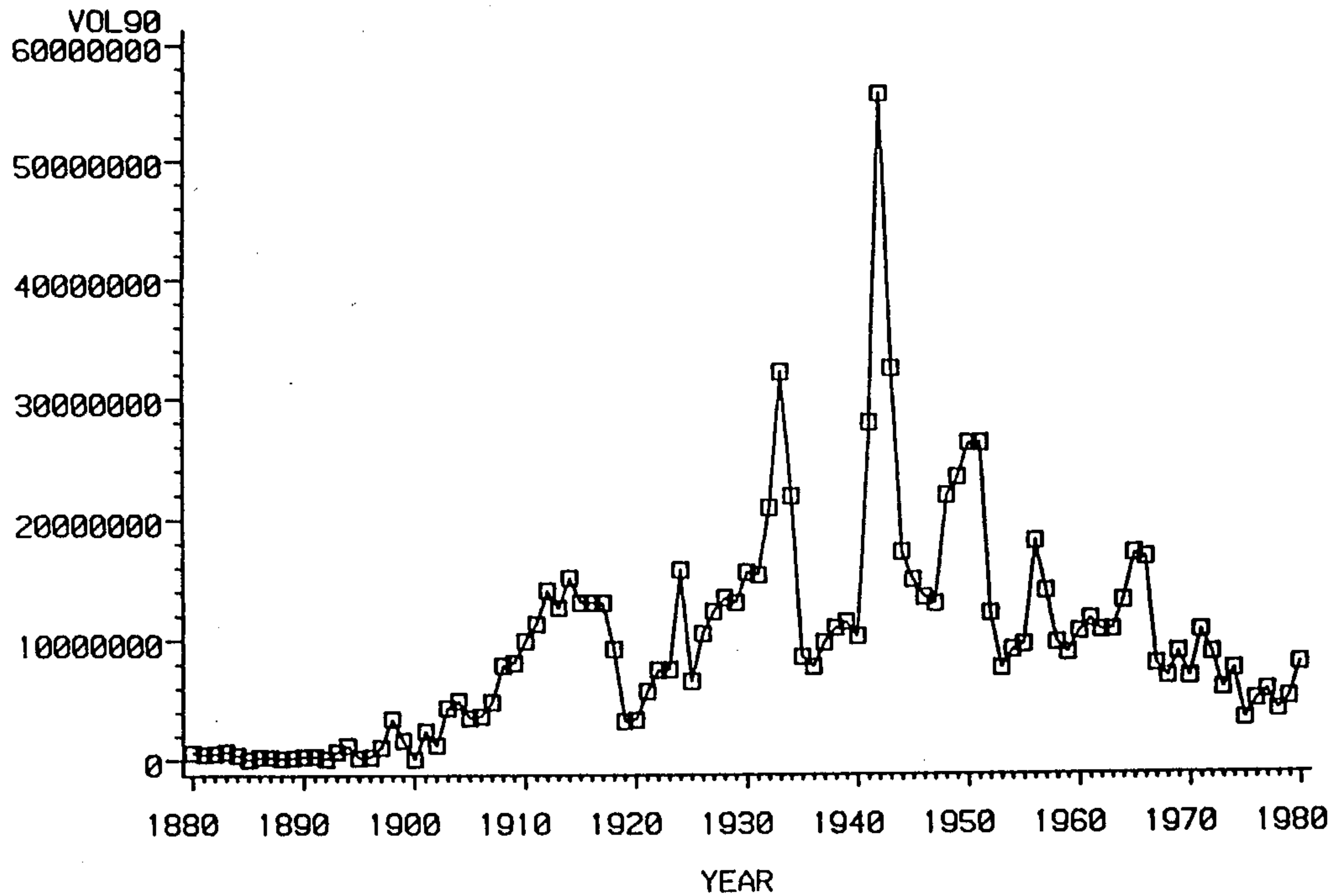


Figure 16. Total volume of material dredged from miles 0-90 in the Delaware River.

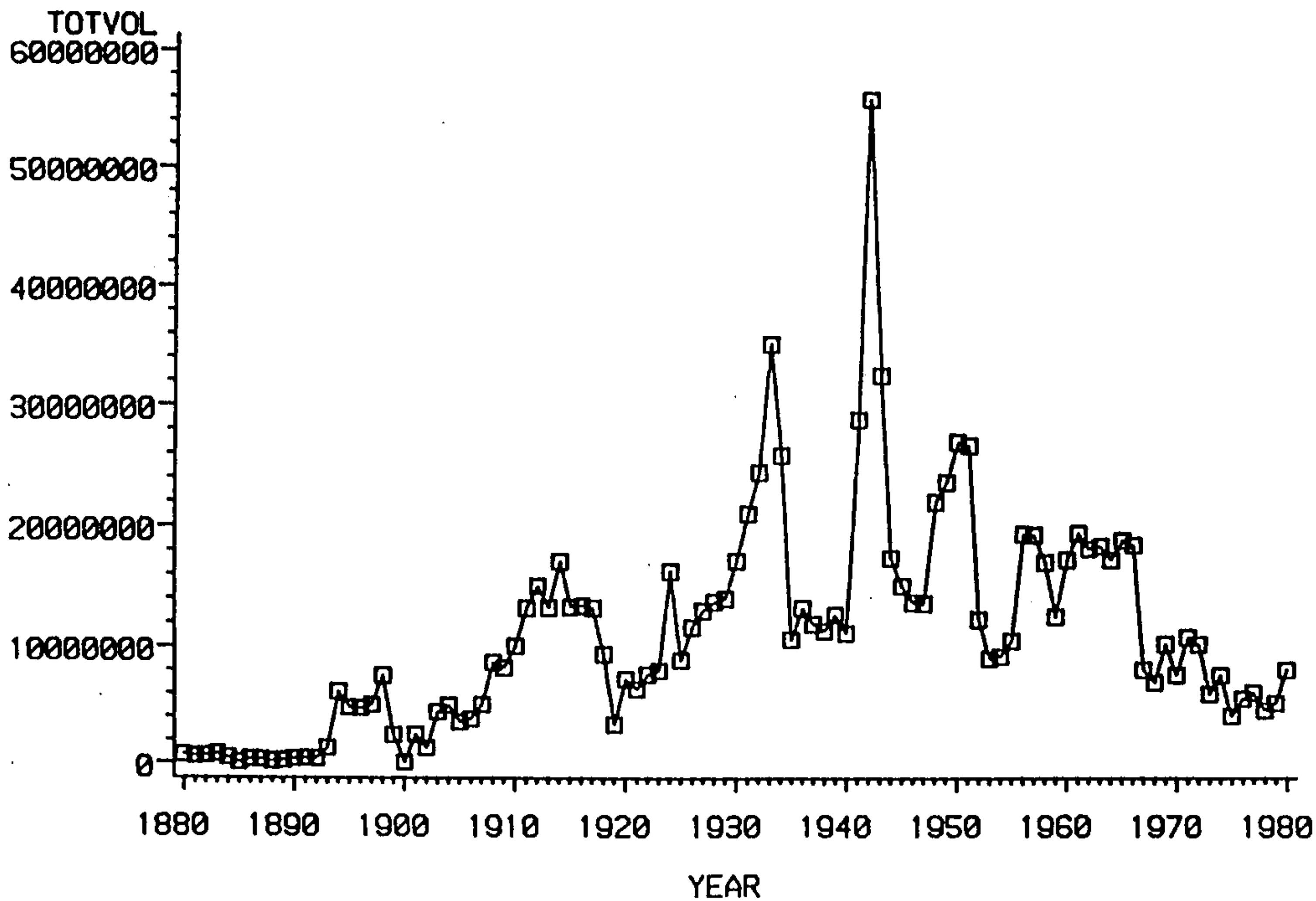


Figure 17. Total volume of material dredged from miles 0-135 in the Delaware River.

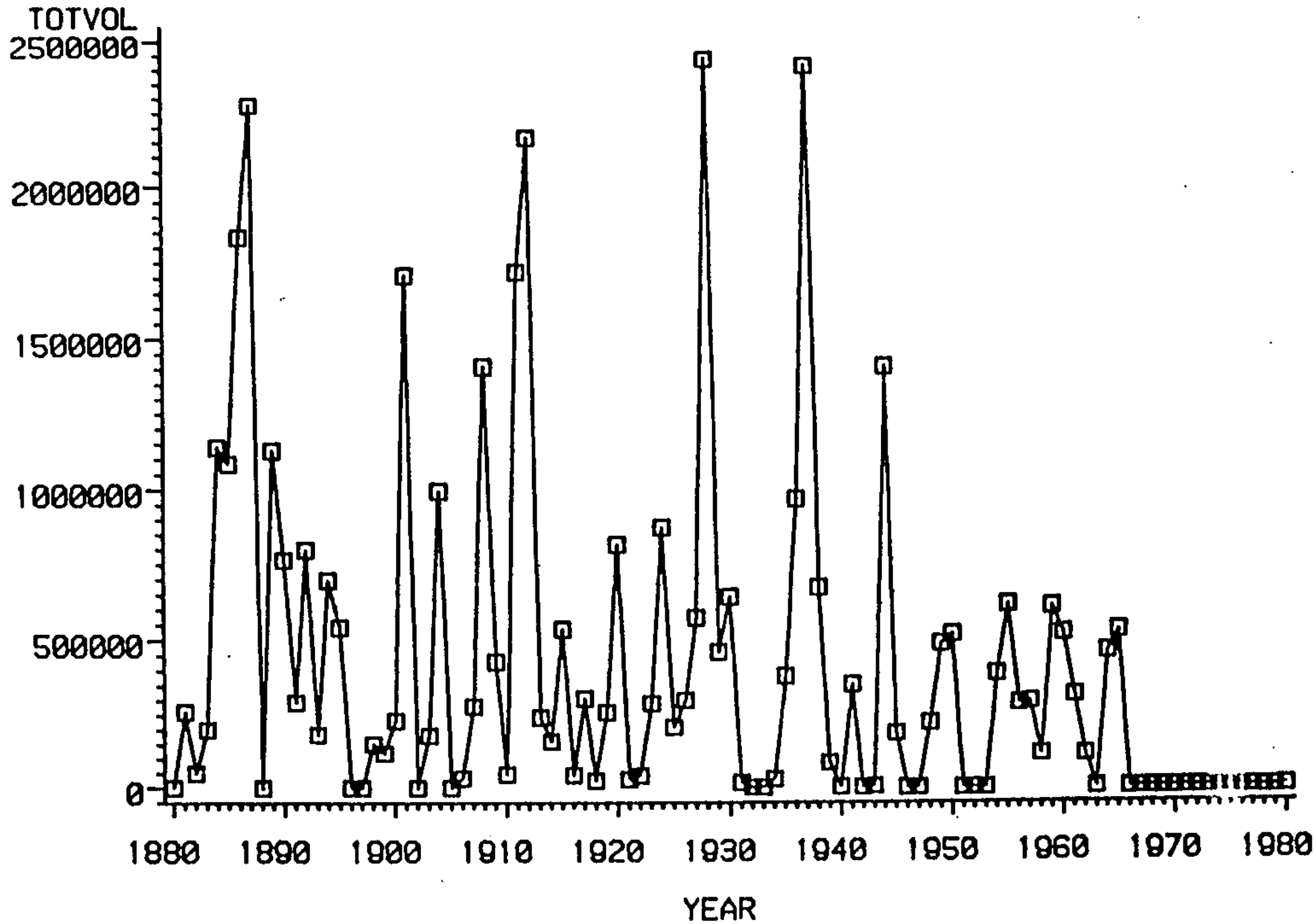


Figure 18. Total volume of material dredged from miles 55-115 in the Potomac River.

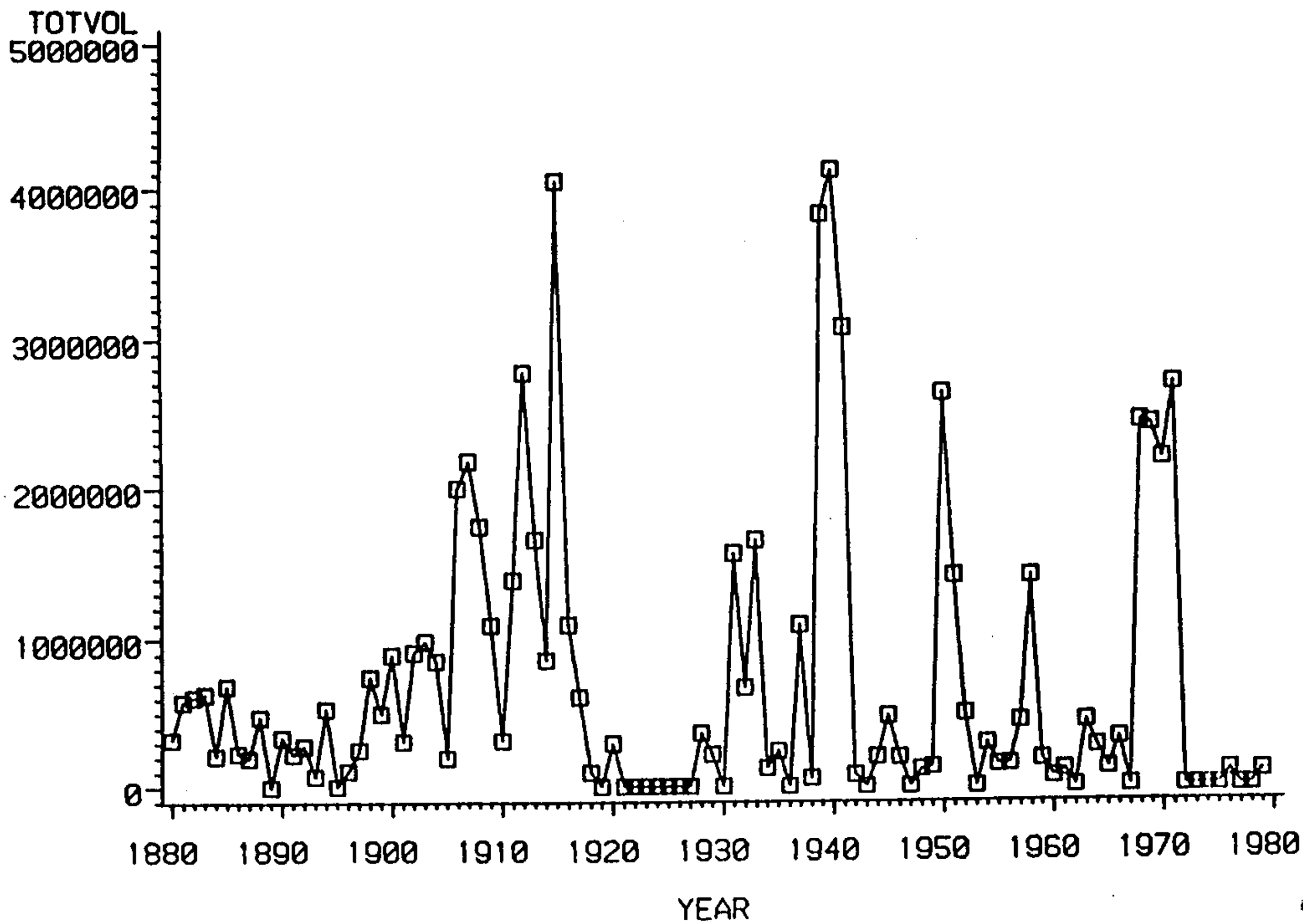


Figure 19. Total volume of material dredged from miles 0-30 in the Narragansett Bay and Providence River and from miles 0-20 in the Sakonnet and Taunton Rivers.

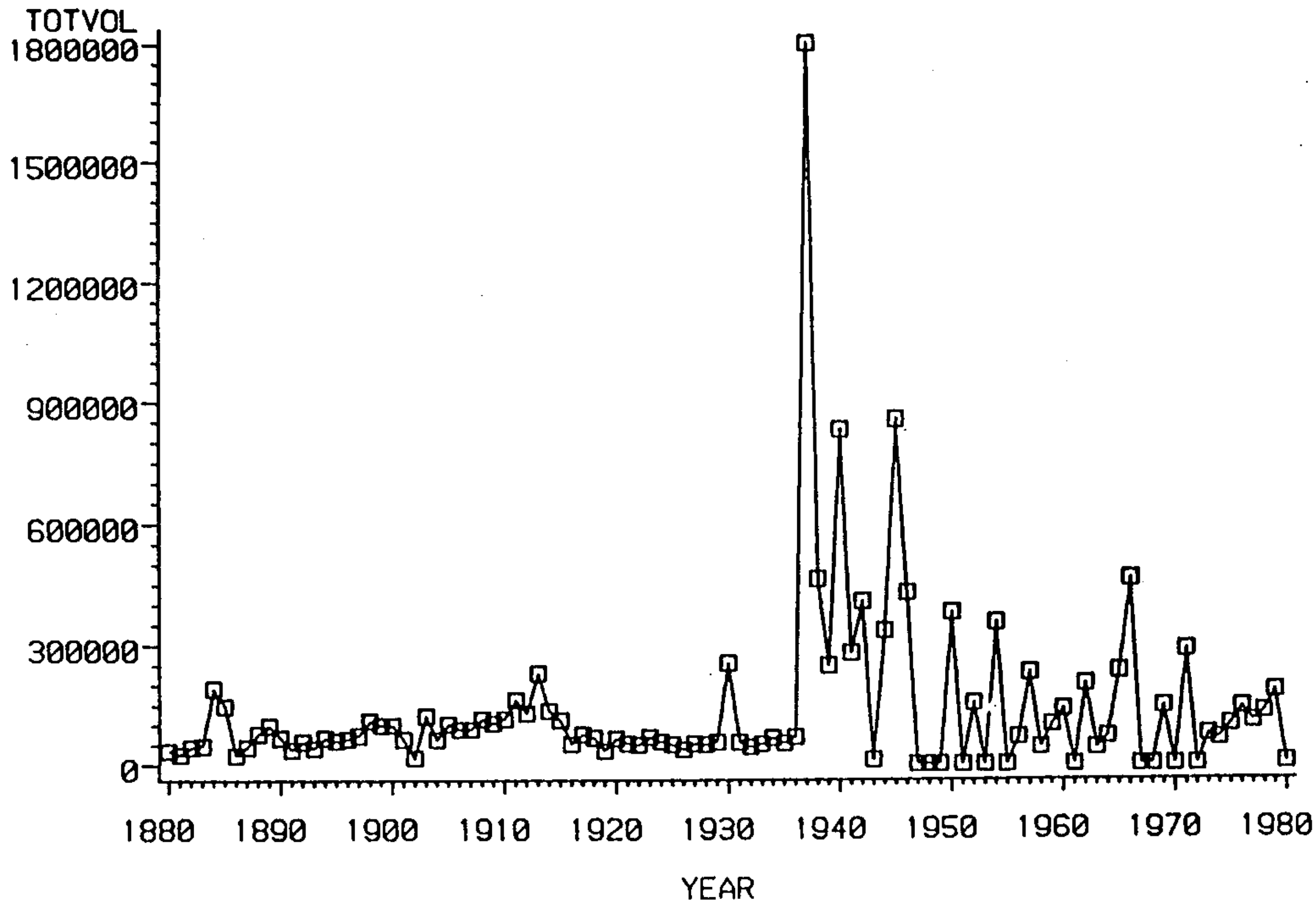


Figure 20. Total volume of material dredged from miles 0-40 in the Connecticut River.

the spatial segments of the remaining estuaries where fishes, regardless of type, generally spawn -- for the Potomac, miles 55-115; for the Narragansett, from the mouth of Narragansett Bay 30 miles up into the Providence River and 20 miles up into the Sakonnet River (including part of the Taunton River); for the Connecticut, beginning at the mouth of the Connecticut River, miles 0-45).

- Dissolved Oxygen (DO) -- Existing long-term DO time series were obtained for the Potomac, Hudson/Raritan, and Delaware estuaries. The timeseries data for the Potomac were the minimum 28-day average summertime DO concentrations at a station near Fort Foote/Woodrow Wilson Bridge, south of Washington, D.C. (Fig. 21). The data were obtained from Conlin (1982) and a letter from the Secretary of the Treasury to the United States Senate. The time-series data for the Delaware were of the minimum average summertime DO concentrations observed across stations located between river miles 48 and 134 (Fig. 22). The data up to 1972 were reported in Kiry (1974), and the 1973 and 1974 values were estimated from more recently collected data (Delaware River Basin Commission, 1976a and b). For the Hudson/Raritan, four separate time series were constructed, and the data used were DO measured as percent saturation, as reported in the 1982 New York Harbor Water Quality Survey. These time series were constructed to reveal DO trends in the Hudson River, Upper New York Bay, Kill Van Kull, and Arthur Kill regions (Figs. 23 to 26, respectively).

- Municipal Sewage Discharges -- Time series were constructed from data on the total volume of sewage discharged, and the biochemical oxygen demand (BOD) loadings, from sewage treatment plants in the Potomac, Hudson/Raritan, and Delaware estuaries. The time series of BOD loadings were included because they reflect trends in sewage treatment. The time series for the Potomac (Figs. 27 and 28) were constructed from data for treatment plants in the Washington, D.C., metropolitan area; these data were obtained from Jaworski et al. (1971) and Clark et al. (1980). Data used to construct the time series for the Hudson/Raritan were obtained from annual reports and files of the Interstate Sanitation Commission, and those for the Delaware, from annual reports of the Philadelphia Water Department and operating reports on file at specific treatment plants. The data were average daily sewage loading in millions of gallons per day (MGD); BOD loading was computed as a weighted average of sewage flows, with weighting factors based on the percent removal of BOD by treatment at each plant. In this manner, BOD loadings are expressed in MGD equivalents and reflect the effects of various levels of treatment on sewage discharges. The weighting factor values were based on the percent removal of BOD reported for individual plants or, when these data were not available, on the typical values for primary and secondary treatment (see Metcalf and Eddy, 1972). The sewage-loading data were representative of over 90% of the plants discharging sewage into the Hudson/Raritan; and the major plant in Camden, N.J., and the three major plants in Philadelphia discharging into the Delaware. For the Hudson/Raritan, sewage and BOD loadings were calculated for three geographic areas: the Hudson River downriver of the Bear Mountain Bridge, East River, and Upper New York Bay; the Arthur Kill, Kill Van Kull, and Newark Bay region; and the Raritan and Sandy

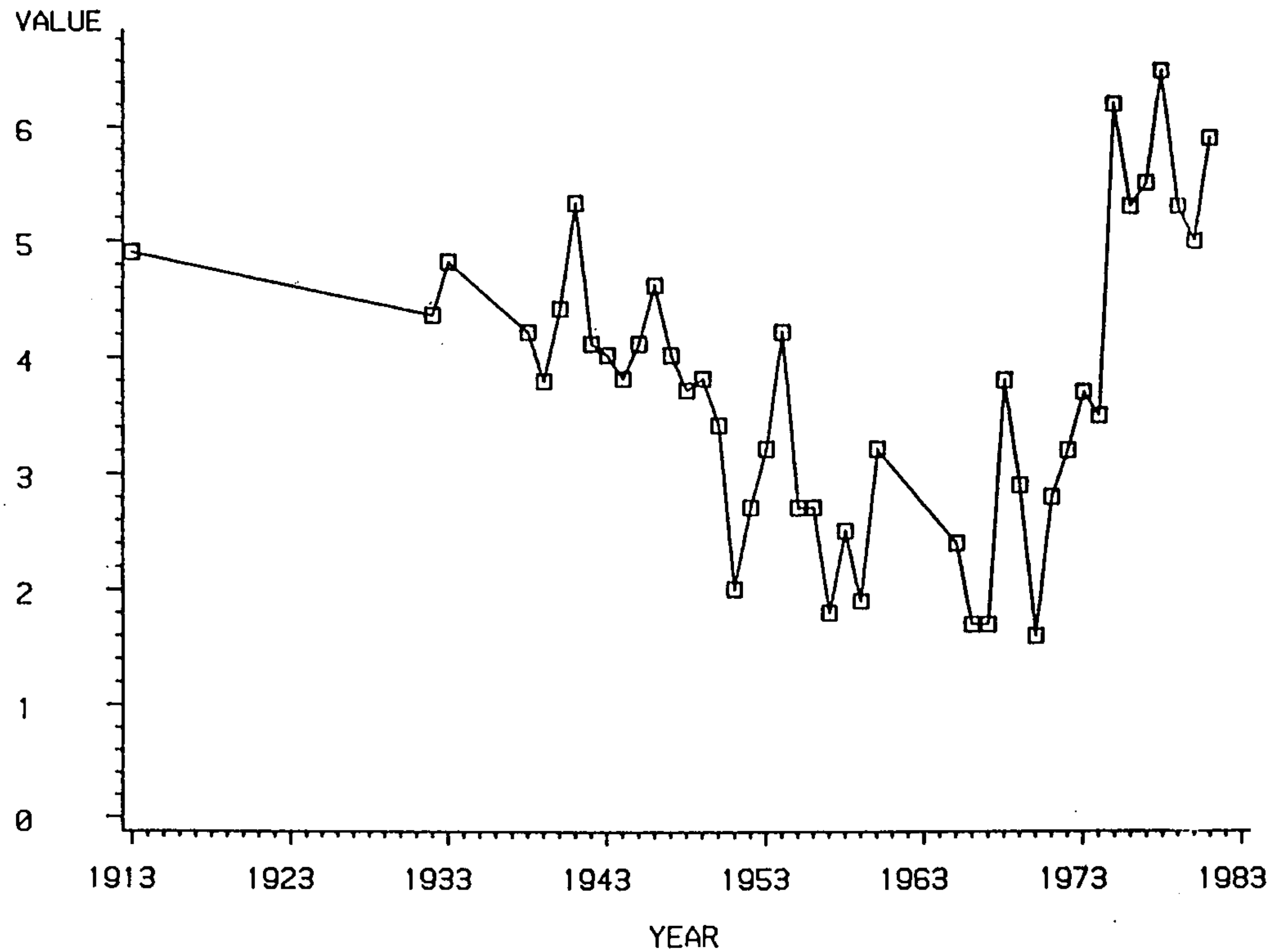


Figure 21. Minimum 28-day average summertime dissolved oxygen (DO) concentration at a sampling station near Fort Foote/Woodrow Wilson Bridge on the Potomac River.

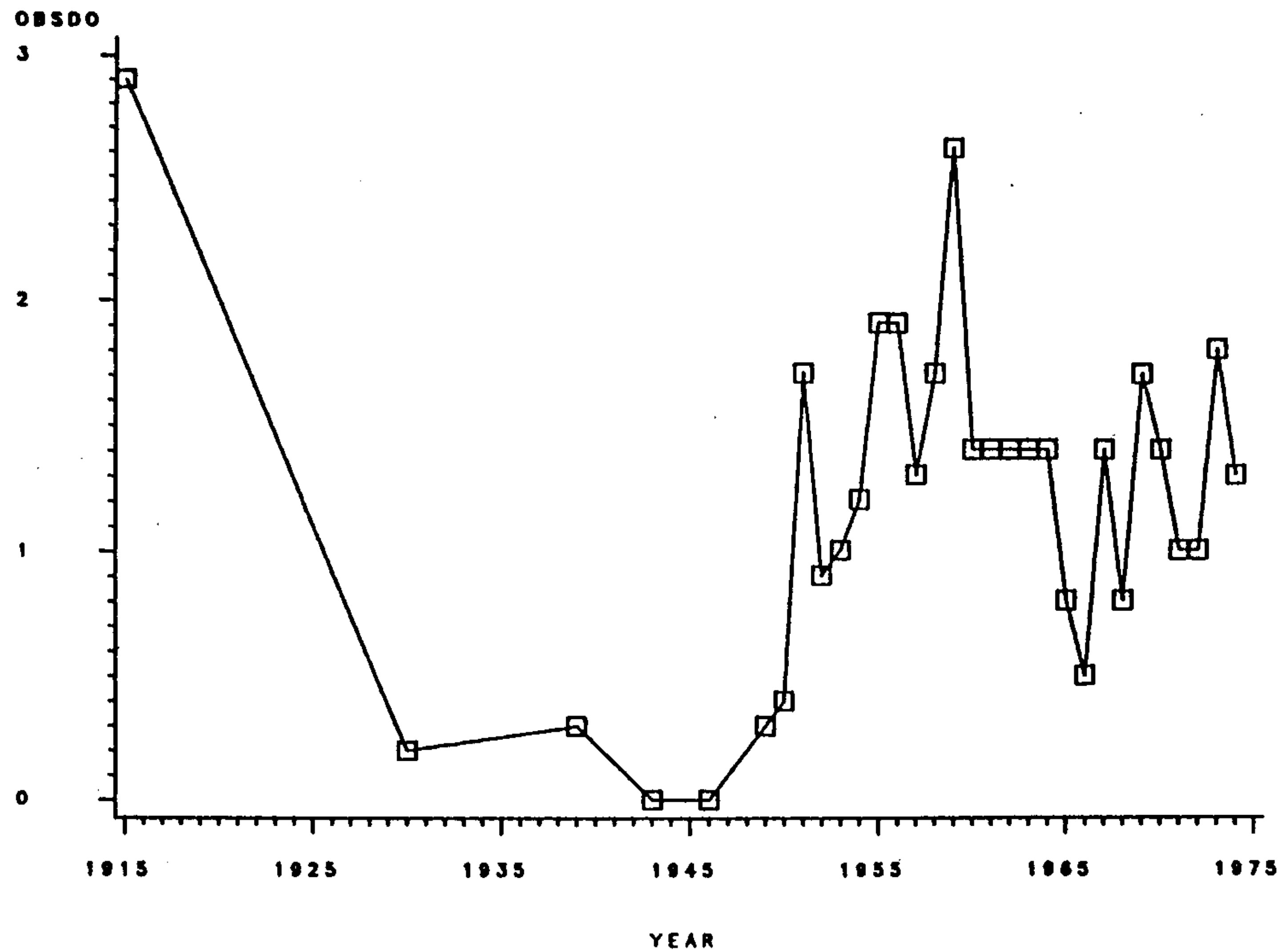


Figure 22. Minimum average summertime DO concentration across sampling stations located between river miles 48 and 134 in the Delaware River.

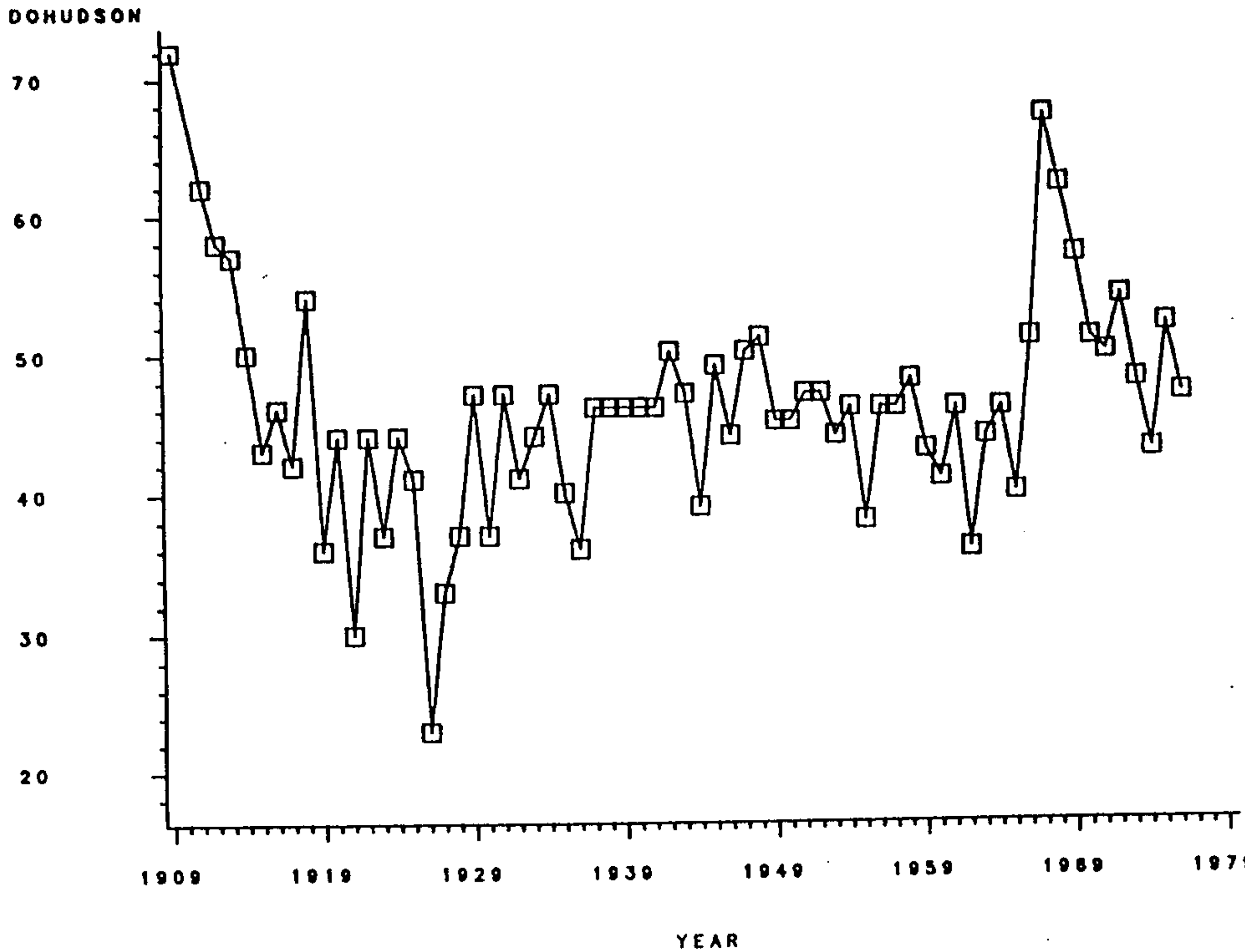


Figure 23. Average DO concentration in the Hudson River.

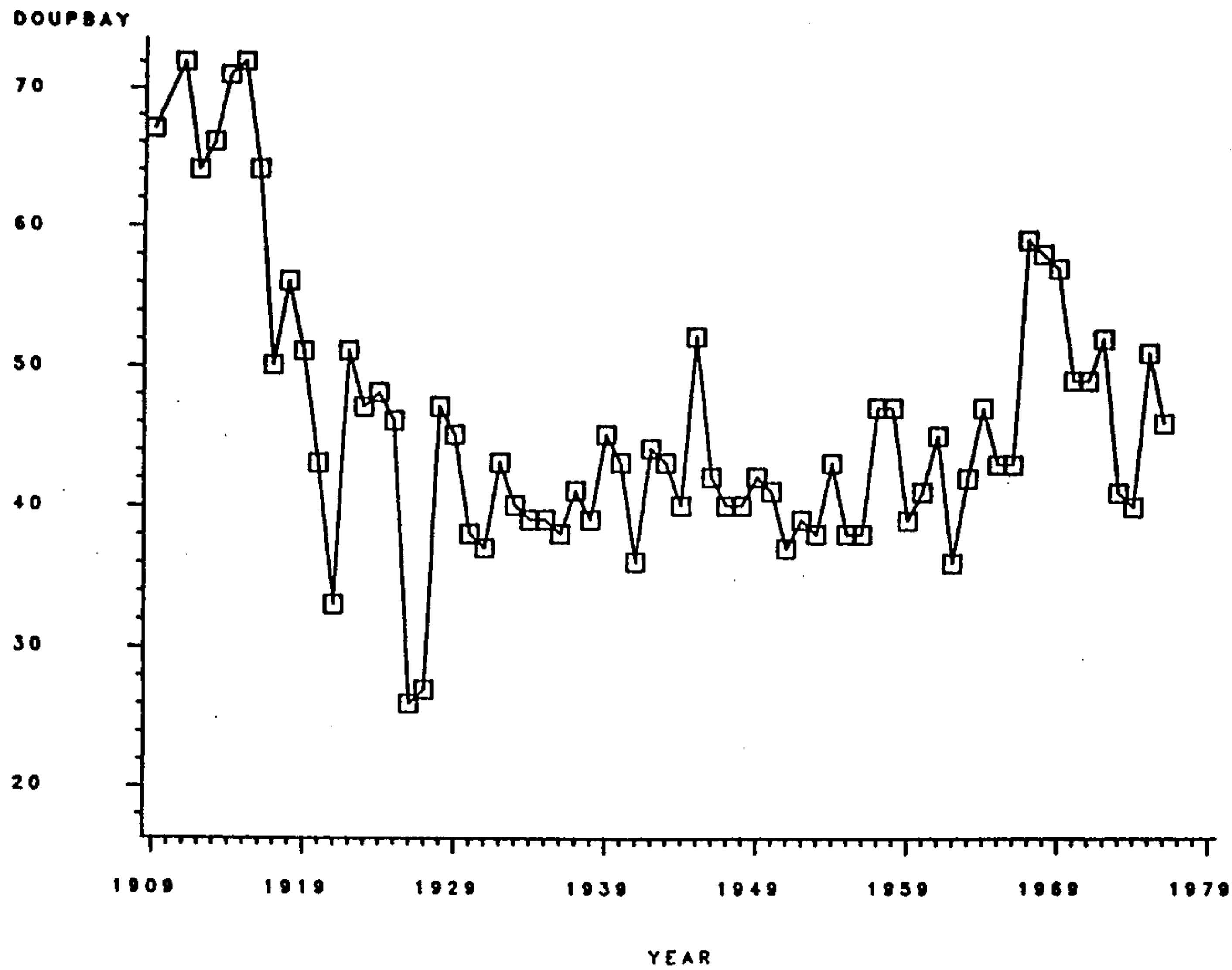


Figure 24. Average DO concentration in the Upper New York Bay.

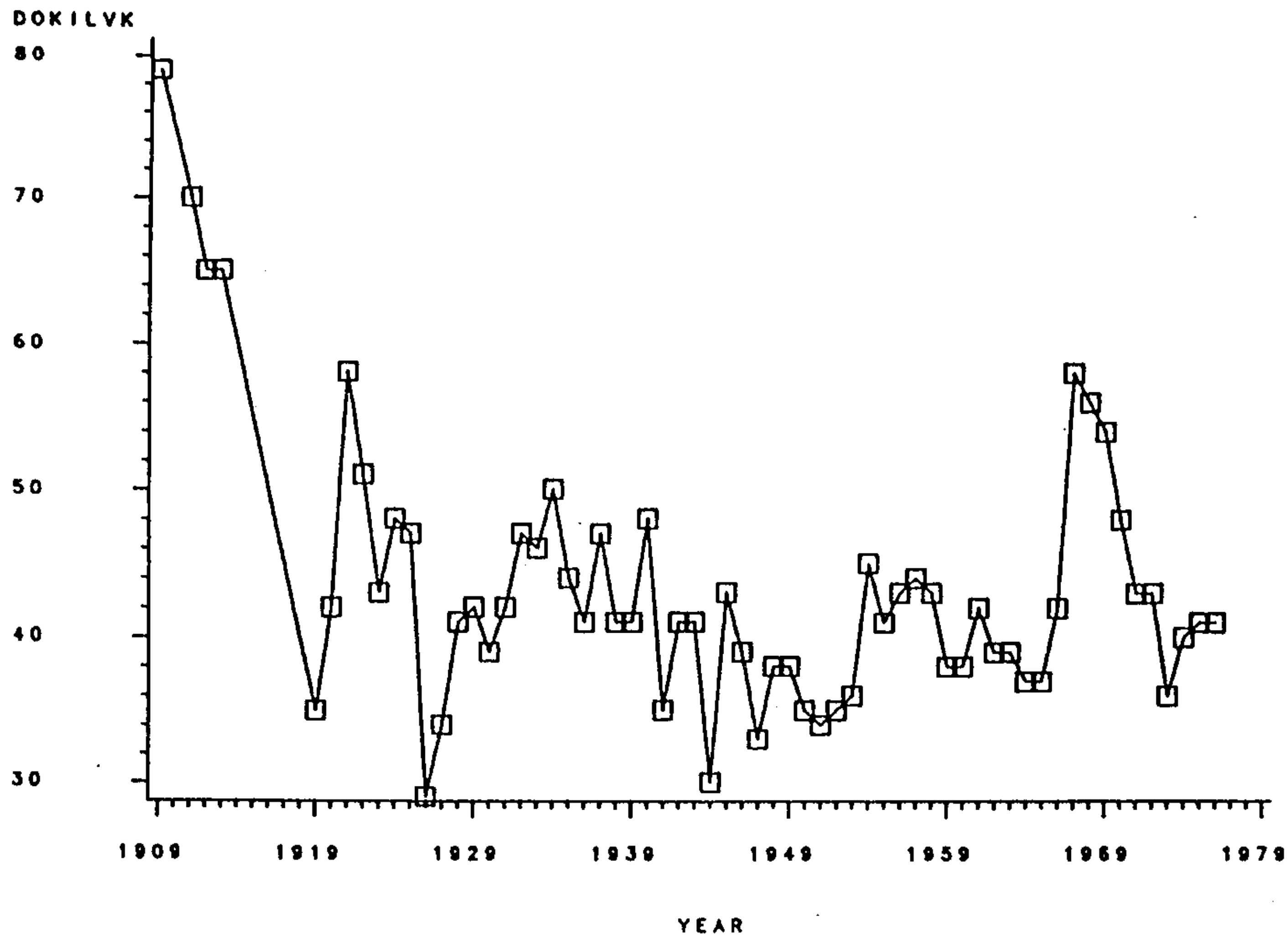


Figure 25. Average DO concentration in the Kill Van Kull.

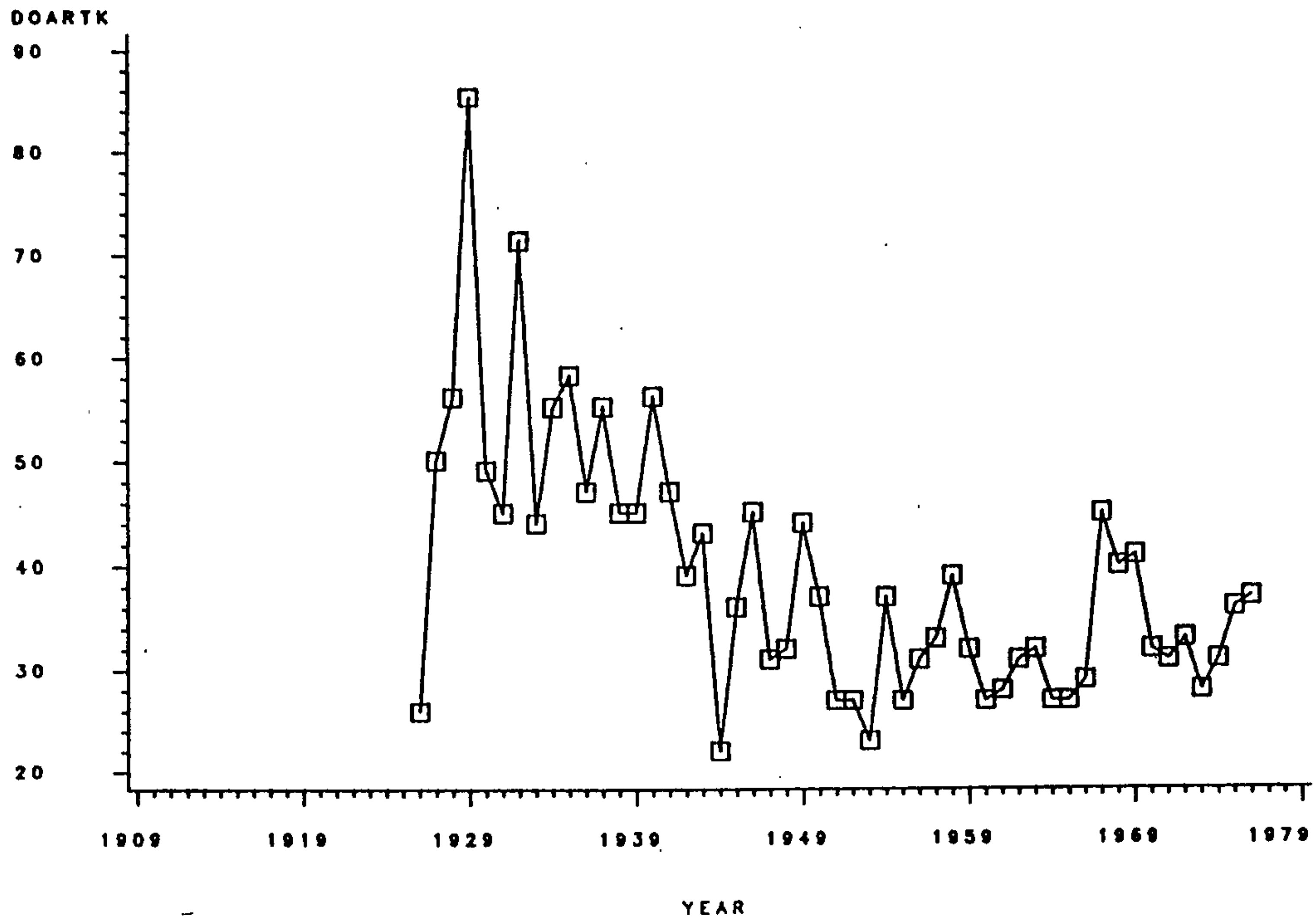


Figure 26. Average DO concentration in the Arthur Kill.

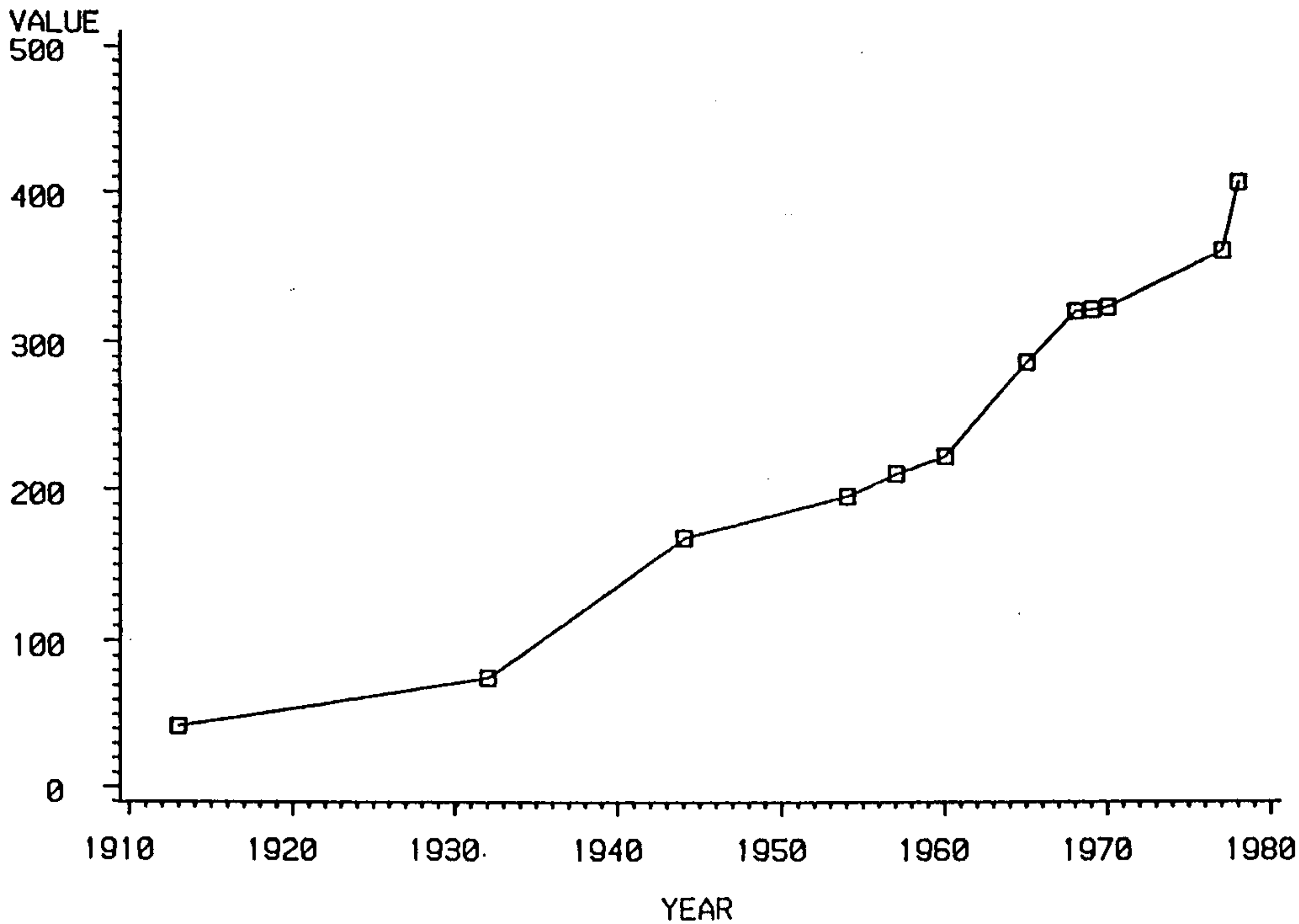


Figure 27. Sewage loading (million gallons per day) from treatment plants that are located in the Washington, D.C., metropolitan area and discharge into the Potomac River.

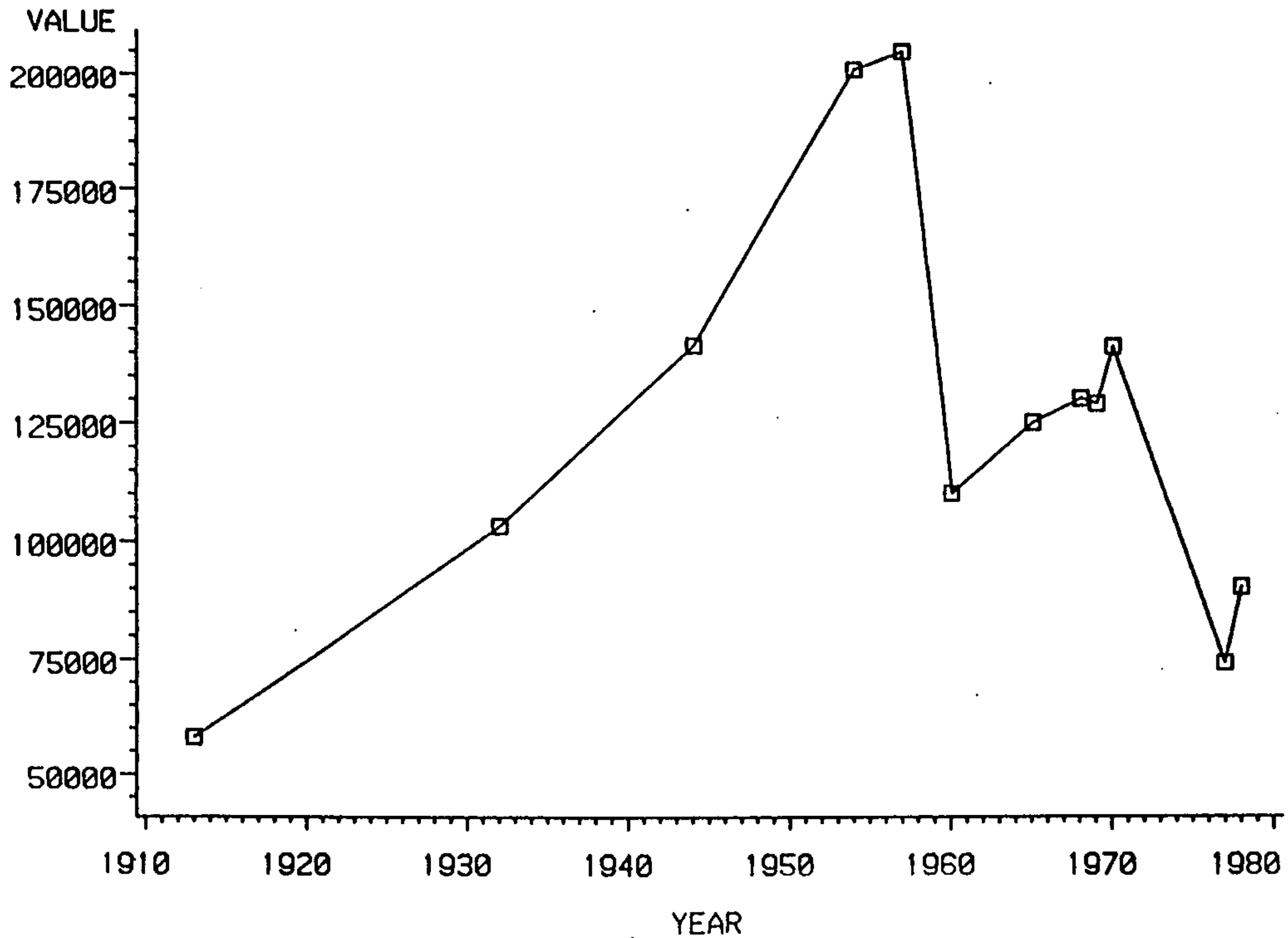


Figure 28. The BOD loading from sewage treatment plants located in the Washington, D.C., metropolitan area and discharging into the Potomac River.

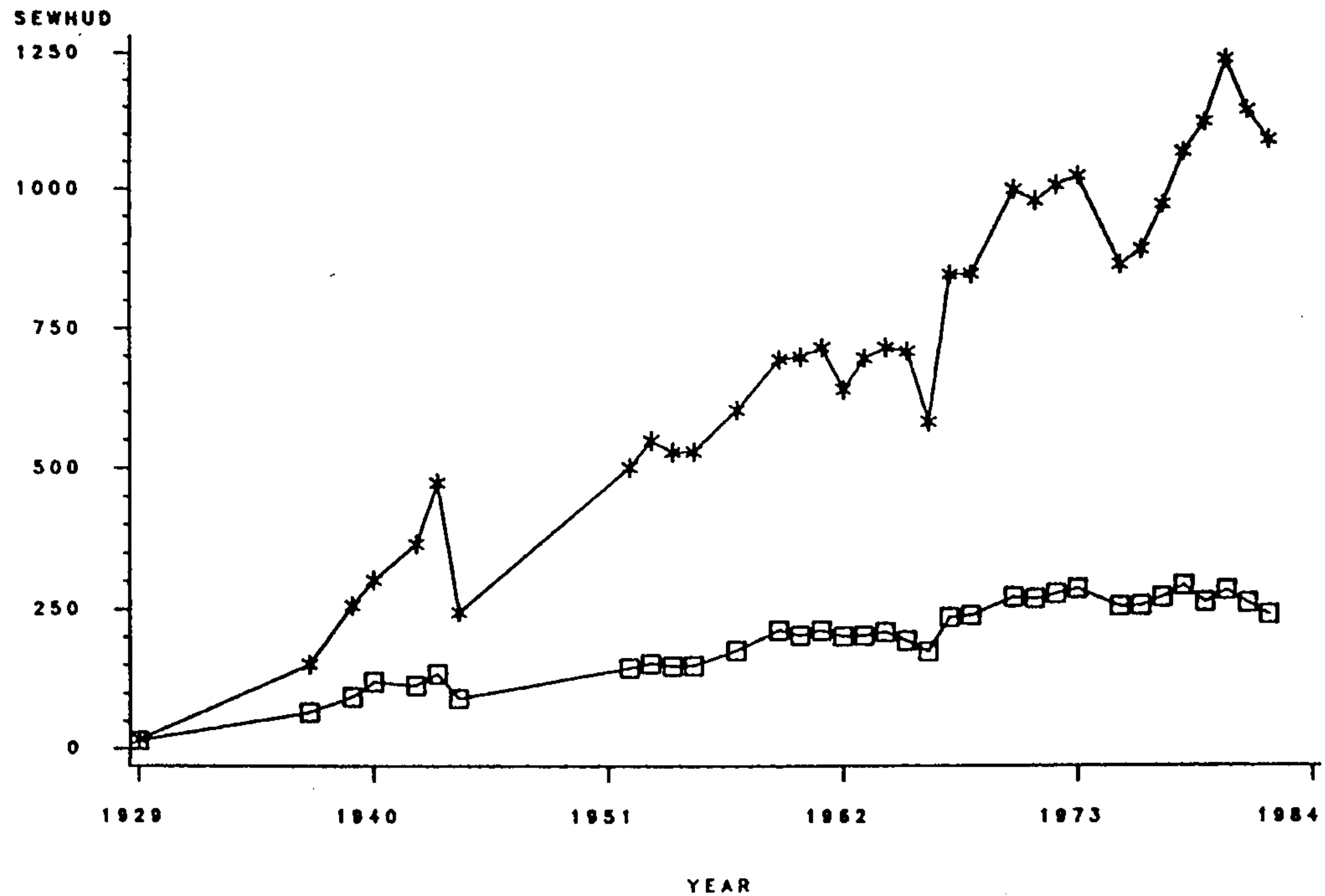


Figure 29. Sewage loading (*) and BOD loading (◻) from treatment plants discharging into the Hudson River downriver of the Bear Mountain Bridge, East River, and Upper New York Bay.

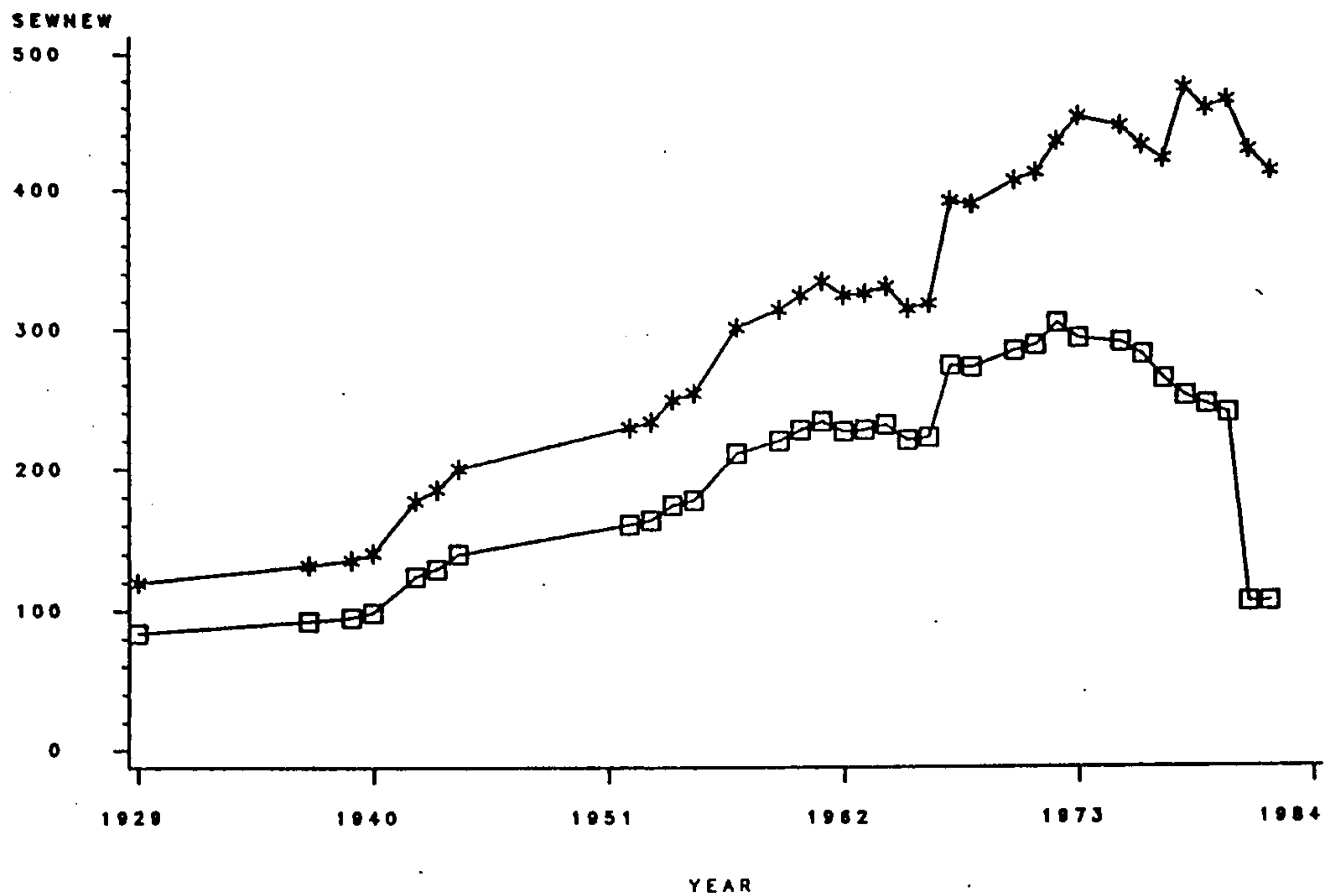


Figure 30. Sewage loading (*) and BOD loading (□) from treatment plants discharging into the Arthur Kill, Kill Van Kull, and Newark Bay areas.

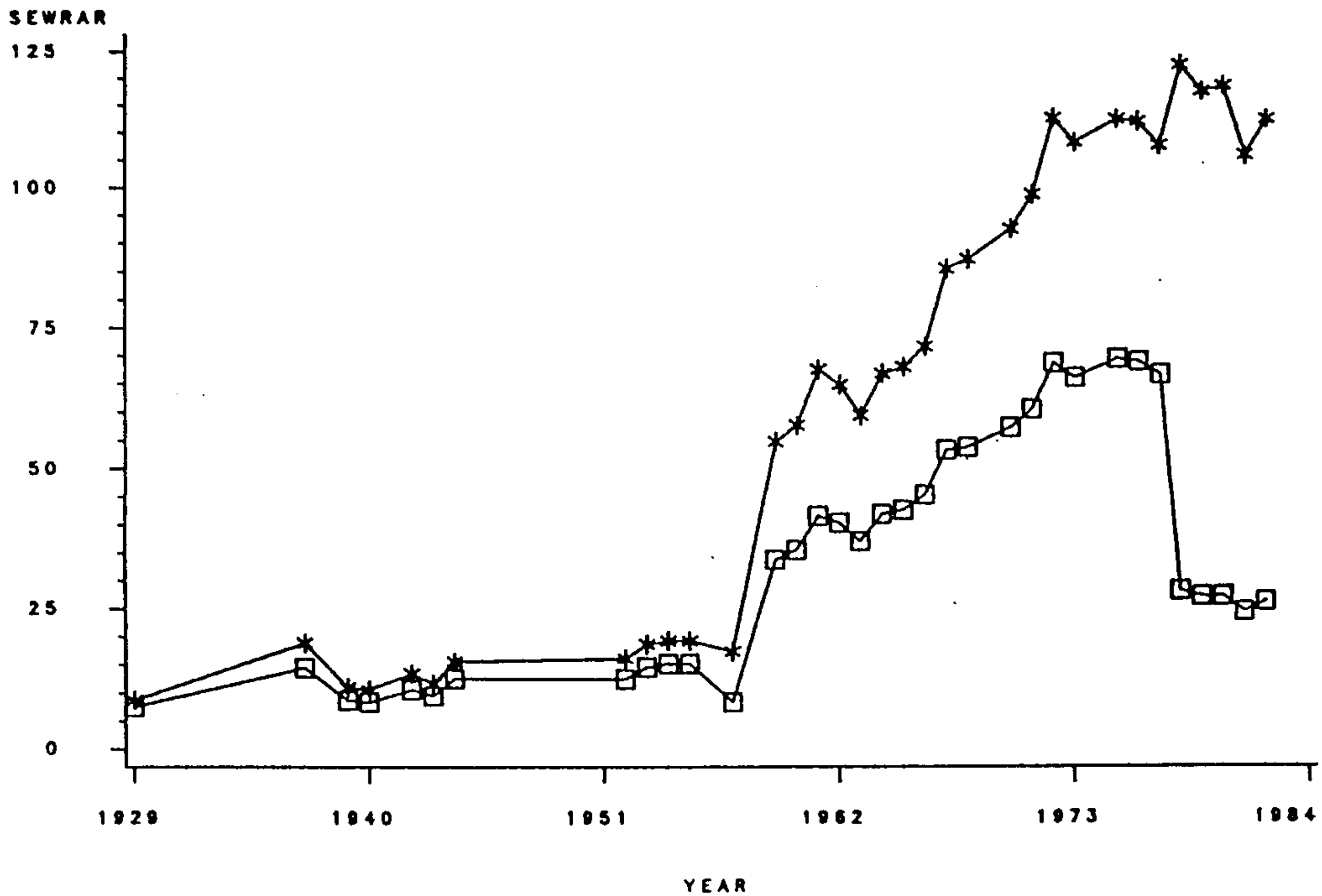


Figure 31. Sewage loading (*) and BOD loading (□) from treatment plants discharging into the Raritan and Sandy Hook Bay areas.

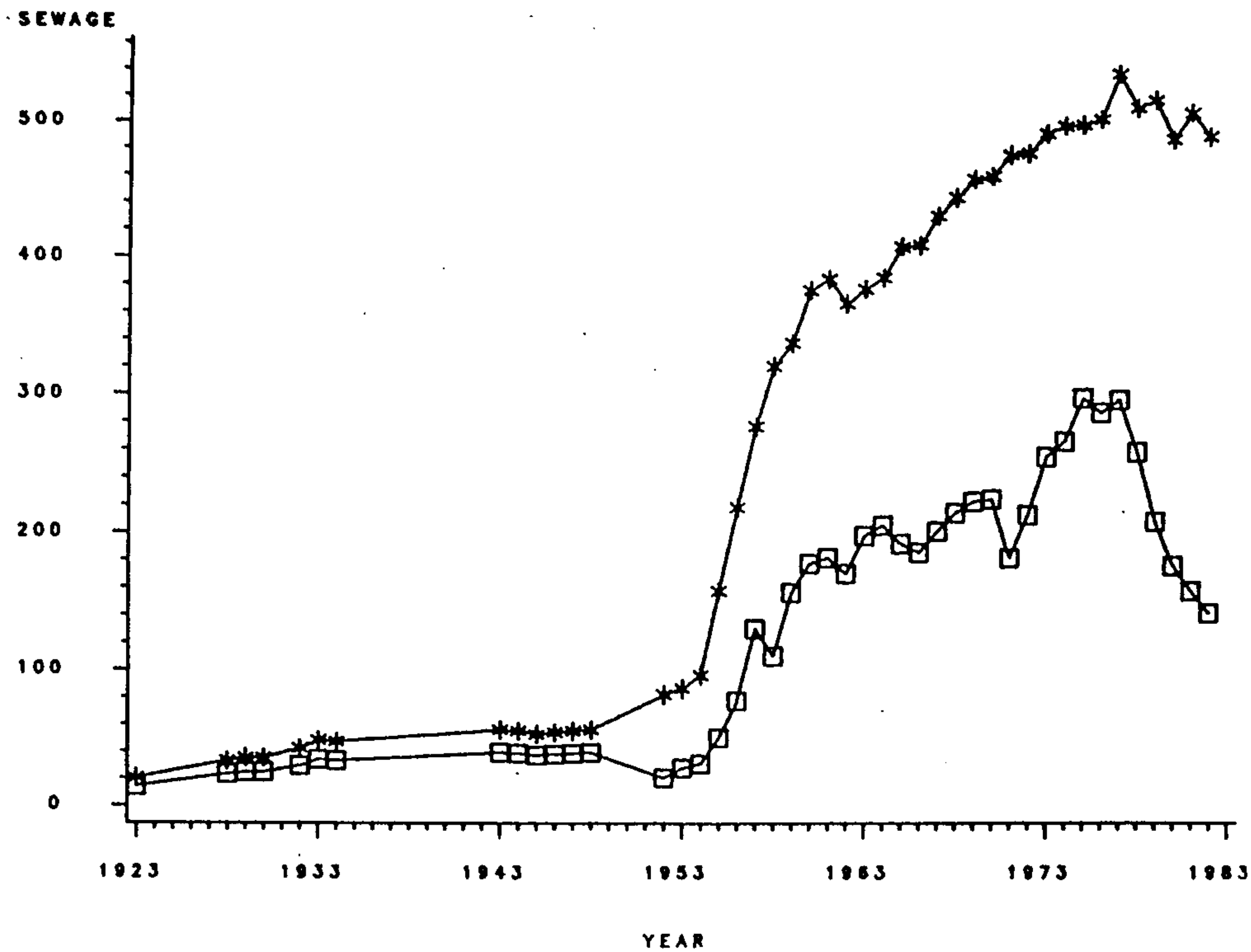


Figure 32. Sewage loading (*) and BOD loading (□) from the major Philadelphia and Camden treatment plants discharging into the Delaware River.

Table 2. Master key to macropollution variables used in the Historical Fisheries/Pollution Program

Variable		
Name	Description	Estuaries to which variable applies[a]
POPULATE	Human population	P,D,H,C,N
TOTVOL	Total volume of dredge material removed from basin	P,D,H,C,N
VOL40	Total volume of dredge material removed from RM[b] 40-165	H
VOL90	Total volume of dredge material removed from RM 0-90	D
VOL135	Total volume of dredge material removed from RM 90-135	D
LODO	Minimum 28-day average summertime dissolved oxygen at Fort Foote	P
MINDO	Minimum average summertime dissolved oxygen between RM 48 and 134	D
DOU	Average dissolved oxygen (upper New York Bay)	H
DOH	Average dissolved oxygen (Hudson River)	H
DOA	Average dissolved oxygen (Arthur Kill)	H
DOK	Average dissolved oxygen (Kill Van Kull)	H
SEWAGE	Total sewage discharged	P,D
BOD	Biochemical oxygen demand (in MGD[c] equivalents) associated with SEWAGE	D

(a) P = Potomac River; D = Delaware River/Bay; H = Hudson/Raritan estuary; C = Connecticut River; N = Narragansett Bay.
(b) RM = river mile.
(c) MGD = millions of gallons per day.

Table 2. (continued)

Variable		
Name	Description	Estuaries to which variable applies[a]
BOD5	Five-day biochemical oxygen demand associated with sewage discharges	P
SEWHUD	Total sewage discharged (Hudson and East Rivers and upper New York Bay)	H
SEWNEW	Total sewage discharged (Newark Bay, Arthur Kill, and Kill Van Kull)	H
SEWRAR	Total sewage discharged (Raritan and Sandy Hook Bays)	H
BODNEW	Biochemical oxygen demand (in MGD equivalents) associated with SEWNEW	H
BODHUD	Biochemical oxygen demand (in MGD equivalents) associated with SEWHUD	H
BODRAR	Biochemical oxygen demand (in MGD equivalents) associated with SEWRAR	H
SIC	Total number of employees in manufacturing	P
IMFARM	Acreage in improved farmland	P,D,H,C,N

3. FISHERIES AND CLIMATE DATA

3.1 Data Collection

The availability of data constrains the development and implementation of analytical techniques that might be used to represent stock dynamics. Analyses that appear well-suited to achieving the program objectives are useless if the necessary data are not available. Because the success of the program depended on reasonable data from which to construct time series, we conducted as exhaustive a search as possible for data on landings, fishing effort, climate, and water quality for the target estuaries and target stocks (Table 3).

For a data set to be useful, it generally should be long term (to permit a useful description of the behavior of the measured variable over time), representative of a defined stock or variable, or both. These criteria provided a basis for evaluating individual data sets for potential usefulness in constructing time series.

We based data collection efforts on the following goals:

- Obtaining data on stock levels (generally acquired from information on landings and fishing effort) for the targeted fisheries within specified estuaries

- Obtaining data on major climatic factors influencing early life cycles (e.g., temperature, salinity, and flow), since many fisheries are known to be influenced by climate.

Initially, our primary interest was to locate long-term annual or monthly data sets (i.e., covering 50-100 years) that were in computer-compatible form. We therefore contacted (by telephone) fisheries workers, fisheries statisticians, hydrologists, and meteorologists employed by federal, state, and private organizations. We found long-term data sets for freshwater discharge, air temperature, and precipitation, as well as piecemeal information covering 50-100 years for 150 water quality variables. Arrangements were made to acquire these data in machine-readable form.

3.1.1 Fisheries data

The specific fisheries data sought were those on annual landings and associated effort for each target estuary-stock combination. Only intermittent landings data, however, were available for the years prior to 1929 (only 8-12 years of data between 1880 and 1928). In addition, no long-term estuary-specific data on fishing effort were available for any of the target estuaries.

Landings data by target estuary were collected from handwritten and published sources maintained by the Resource Statistics Division of NOAA. These data generally covered only the period 1945-1976; those for the Potomac River, however, covered the period 1929-1976. Estuary-specific landings data for years prior to 1945 were estimated from published county data as the sum of landings for all counties bordering the target estuary. Although this method introduces some potential for error, in that several of these counties also

Table 3. Main fisheries, climate, and water quality variables on which data were sought

Fisheries Variables[a]	Climate Variables[d]	Water Quality Variables
Landings by estuary[b]	Air temperature	Turbidity
Landings by state[c]	Water temperature	Seston
Fishing effort by state	Precipitation	Biochemical oxygen demand
Catch by gear by state	Freshwater discharge	Dissolved oxygen
Cost per pound by state	Wind speed and direction	Synthetic organics
		Nutrients
		Heavy metals

[a] All fisheries data are species specific.
[b] Estuaries are Hudson/Raritan River, Potomac River, Delaware River, Connecticut River, and Narragansett Bay.
[c] States are Virginia, Maryland, Delaware, Pennsylvania, New Jersey, New York, Connecticut, and Rhode Island.
[d] All climate and water quality data are station specific. Stations are located throughout estuarine watersheds.

border other major bodies of water (e.g., Cape May County, NJ, borders both Delaware Bay and the Atlantic Ocean), these estimates are the best data available for estuary-specific landings prior to 1945. Thus landings data for the target fisheries were gathered for all years in which surveys were conducted from 1880 to 1976 (Table 4). No reliable fisheries data, other than occasional anecdotal information, are available for years prior to 1880.

No data on estuary-specific fishing effort were available other than those in effort records for the Potomac River since 1962 (Potomac River Fisheries Commission, pers. comm.). Therefore, estuary-specific effort or estuary-specific catch-per-unit effort was estimated from data on statewide landings effort, catch by gear, and cost per pound. These state-specific data for the period 1880-1976 were collected primarily from microfiche records of the series "Fisheries Statistics of the United States" (1871-1976). The fisheries and effort variables searched are shown in Table 5. All data were hand transcribed, keypunched into computer-compatible format, and entered into the Martin Marietta Environmental Systems/NOAA database. This data-collection effort encompassed 3,706 time-series records and 226,066 individual data records, a significant expansion over its original scope because of the lack of estuary-specific effort data.

3.1.2 Climate data

For each target estuarine watershed, climate stations were selected from station location maps and record period lists provided by the National Climate Center in Asheville, NC; the stations selected are listed in Table 6. Data on monthly mean precipitation and air temperature were received in computer-compatible form from the National Climate Center's Environmental Data Information Service for all stations of interest, generally for the period 1930-1980. In addition, data were received on maximum and minimum air temperature, deviations from long-term normal air temperature and precipitation, total snowfall, and heating and cooling degree-days, but the observations were too intermittent for defensible time series to be constructed from these data.

Searches were initiated for data on air temperature and precipitation at each target station for the period 1880-1930, as well as for other periods missing from records for individual stations. Microfiche and photocopied records for 1880-1930 were collected from climatic summaries which are compiled annually for each state. All data were hand transcribed, keypunched into computer-compatible form, and merged with the existing climatic data in the Martin Marietta/NOAA database. The years in which data on air temperature and precipitation were available for each station are listed in Table 7. This data-collection effort encompassed about 180,000 individual data records, which were used to construct 150 annual, 600 seasonal, and 1,800 monthly time series.

Climatic data collected in addition to those on temperature and precipitation included data on wind speed and direction along the coastline near the target estuarine locations. Wind data were gathered for areas characteristic of specific target estuaries as well as for areas characteristic of oceanic

Table 4. Years for which annual data are available on landings, catch-by-gear, cost per pound, and associated fishing effort for target locations (estuaries and states[a])

Target Location[a]	Years
Narragansett Bay, State of Rhode Island, Connecticut River, State of Connecticut	1880, 1887-1889, 1897-1898, 1902, 1905, 1908, 1910, 1919, 1924-1933, 1935, 1937-1940, 1942-1976
State of New York, Hudson-Raritan, State of New Jersey	1880, 1887-1892, 1897-1898, 1901, 1904, 1908, 1915, 1921, 1926, 1929-1933, 1935, 1937-1940, 1942-1976
State of Delaware, Delaware Bay, State of Maryland, State of Virginia, Potomac River	1880, 1887-1892, 1897, 1901, 1904, 1908, 1920, 1925, 1929-1942, 1944-1976

[a]For estuaries, only landings data are included; for states, all categories of fisheries data included.

Table 5. Fisheries and effort variables on which data were sought for each target location

Fishery	Effort Variable and (Unit)
<u>Finfishes</u>	
Alewife	Fishermen (no.)
American pollock	Vessels (no.)
Sturgeon	Capacity of vessels (tons)
American shad	Mackerel purse seine (no.)
Menhaden	Mackerel purse seine (sq. yd)
Sea herring	Menhaden purse seine (no.)
Weakfish (squeteague)	Menhaden purse seine (sq. yd)
Atlantic cod	Other purse seine (no.)
Spot	Other purse seine (sq. yd)
Yellowtail flounder	Haul seine (no.)
Haddock	Haul seine (yd)
Silver hake (whiting)	Stop seine (no.)
White perch	Stop seine (yd)
Striped bass	Anchor gill net (no.)
Atlantic croaker	Anchor gill net (sq. yd)
Smelt	Drift gill net (no.)
Summer flounder (fluke)	Drift gill net (sq. yd)
Butterfish	Stake gill net (no.)
Bluefish	Stake gill net (sq. yd)
Winter flounder (blackback)	Runaround gill net (no.)
Atlantic mackerel	Runaround gill net (sq. yd)
Windowpane flounder (sand dab)	Hand line (no.)
Scup	Trawl line (no.)
Tautog	Trotline (no.)
Red hake (squirrel hake or ling)	Pound net (no.)
White hake	Floating traps (no.)
Tomcod (frostfish)	Fyke net (no.)
Flounders (general)	Dip net (no.)
Hakes (general)	Otter trawl (no.)
Carp	Eel pot (no.)
Catfish	Crab pot (no.)
Eels	Lobster pot (no.)
	Clam dredge (no.)

Table 5. (continued)

Fishery	Effort Variable and (Unit)
Shellfishes	
Bay scallop	Oyster dredge (no.)
Blue crab	Scallop dredge (no.)
American oyster	Tongs (no.)
American lobster	Rakes (no.)
Hard clam	Fish pots (no.)
Soft clam	Weirs (no.)
	Stop net (no.)
	Stop net (sq yds)
	Scrapes (no.)
	By hand (no. of licenses)
	Crab dredge (no.)
	Gill nets (combined no.)
	Trammel net (no.)
	Pick (no.)
	Crab net (no.)

Table 6. Climate stations, by target estuary, at which all climate data were recorded

Potomac River	Delaware River	Hudson/ Raritan	Connecticut River	Narragansett Bay
Solomons, MD	Dover, DE	Freehold, NJ	Storrs, CT	New Bedford, MA
La Plata, MD	Milford, DE	Sandy Hook, NJ	Middletown, CT	Taunton, MA
Beltsville, MD	Newark, DE	Flemington, NJ	Hartford, CT	Nantucket, MA
Great Falls, MD	Cape May, NJ	Jersey City, NJ	Amherst, MA	Providence, RI
Rockville, MD	Belleplain, NJ	Newark, NJ	Springfield, MA	Kingston, RI
Frederick, MD	Moorestown, NJ	Plainfield, NJ	Gardner, MA	Newport, RI
Hancock, MD	Trenton, NJ	Boonton, NJ	Vernon, VT	Block Is., RI
Oakland, MD	Lambertville, NJ	Charlotteburg, NJ	Cavendish, VT	
Cumberland, MD	Belvidere, NJ	Scarsdale, NY	St. Johnsberry, VT	
Washington, DC	Sussex, NJ	New York, NY	Keene, NH	
Manassas, VA	Newton, NJ	West Point, NY	Hanover, NH	
Lincoln, VA	Philadelphia, PA	Albany, NY	Bethlehem, NH	
Mt. Weather, VA	Stroudsburg, PA	Little Falls, NY	Errol, NH	
Fredericksburg, VA	Matamoras, PA	Schenectady, NY	First Conn Lake, NH	
Woodstock, VA	Hawley, PA	Gloversville, NY	Greenport, NY	
Dale Enterprise, VA	Pleasant Mt., PA	Trenton Falls, NY		
		Smith Basin, NY		
		Indian Lake, NY		

Table 7. Years for which data from each climate station are and are not available

Estuary and Station Location	Years Data Available Precip.	Air Temp.	Years Data Missing
POTOMAC RIVER			
SOLOMONS, MD	1889-1981	1896-1981	1880-1888 (P)[a]
LA PLATA, MD	1889-1981	1896-1981	1880-1888 (P)
BELTSVILLE, MD	1880-1981	1896-1981	
GREAT FALLS, MD	1880-1981	1896-1981	
ROCKVILLE, MD	1880-1981	1896-1981	
FREDERICK, MD	1880-1980	1896-1981	
HANCOCK, MD	1880-1981	1896-1981	
OAKLAND, MD	1880-1981	1896-1981	
CUMBERLAND, MD	1880-1980	1896-1981	
WASHINGTON, DC	1880-1981	1896-1981	
MANASSAS, VA	1880-1886 1895-1981	1896-1981	1887-1894 (P)
LINCOLN, VA	1891-1981	1896-1981	1880-1890 (P)
MOUNT WEATHER, VA	1891-1981	1896-1981	1880-1890 (P)
FREDRICKSBURG, VA	1893-1981	1896-1981	1880-1892 (P)
WOODSTOCK, VA	1889-1981	1896-1981	1880-1888 (P)
DALE ENTERPRISE, VA	1880-1981	1896-1981	

[a] (P) Precipitation
[b] (A) Air temperature

Table 7. (continued)

Estuary and Station Location	Years Data Available Precip.	Air Temp.	Years Data Missing
NARRAGANSETT BAY			
NEW BEDFORD, MA	1880-1981	1896-1981	
TAUNTON, MA	1880-1981	1896-1981	
NANTUCKET, MA	1880-1981	1896-1981	
PROVIDENCE, RI	1880-1981	1896-1981	
KINGSTON, RI	1889-1981	1896-1981	1880-1888 (P)[a]
NEWPORT, RI	1882-1946 1957-1981	1896-1981	1880-1881 (P) 1947-1956 (P)
BLOCK ISLAND, RI	1880-1981	1896-1981	
CONNECTICUT RIVER			
STORRS, CT	1888-1981	1896-1981	1880-1887 (P)
MIDDLETOWN, CT	1880-1928 1931-1981	1896-1981	1929-1930 (P)
HARTFORD, CT	1880-1930 1932-1981	1896-1981	1931 (P)
AMHERST, MA	1880-1981	1896-1981	
SPRINGFIELD, MA	1880-1960	1896-1981	1961-1981 (P)
GARDNER, MA	1907-1981	1896-1981	1880-1906 (P)
VERNON, VT	1886-1981	1896-1981	1880-1885 (P)
CAVENDISH, VT	1903-1981	1896-1981	1880-1902 (P)
ST. JOHNSBERRY, VT	1894-1981	1896-1981	1880-1893 (P)
KEENE, NH	1892-1981	1896-1981	1880-1891 (P)
HANOVER, NH	1880-1981	1896-1981	
BETHLEHEM, NH	1893-1981	1896-1981	1880-1892 (P)

Table 7. (continued)

Estuary and Station Location	Years Data Available Precip.	Air Temp.	Years Data Missing
CONNECTICUT RIVER (CONTINUED)			
ERROL, NH	1885-1981	1896-1981	1880-1884 (P)
FIRST CONN LAKE, NH	1880-1981	1896-1981	
GREENPORT, NY	1899-1981	1899-1981	1880-1898 (P)
DELAWARE RIVER			
DOVER, DE	1880-1981	1896 1898-1899 1906-1916 1919-1981	1897 (A)[b] 1899-1905 (A) 1917-1918 (A)
MILFORD, DE	1880-1981	1896-1899 1901-1981	1900 (A)
NEWARK, DE	1894-1981	1896-1981	1880-1893 (P)
CAPE MAY, NJ	1880-1981	1896-1981	
BELLEPLAIN, NJ	1892-1981	1896-1981	1880-1891 (P)
MOORESTOWN, NJ	1880-1981	1896-1981	
TRENTON, NJ	1880-1981	1896-1981	
LAMBERTVILLE, NJ	1887-1981	1896-1981	1880-1886 (P)
BELVIDERE, NJ	1891-1981	1896-1981	1880-1890 (P)
SUSSEX, NJ	1891-1981	1896-1981	1880-1890 (P)
NEWTON, NJ	1882-1981	1896-1981	1880-1881 (P)
PHILADELPHIA, PA	1880-1981	1896-1981	
STROUDSBURG, PA	1889-1981	1896-1981	1880-1888 (P)
MATAMORAS, PA	1880-1981	1890-1981	
HAWLEY, PA	1880-1981	1896-1981	
PLEASANT MT., PA	1880-1981	1896-1981	
GRAHAMSVILLE, NY	1880-1981		1896-1981 (A)

Table 7. (continued)

Estuary and Station Location	Years Data Available Precip.	Air Temp.	Years Data Missing
HUDSON RIVER-RARITAN RIVER			
FREEHOLD, NJ	1880-1981	1896-1981	
SANDY HOOK, NJ	1880-1981	1896-1981	
FLEMINGTON, NJ	1887-1981	1896-1981	1880-1886 (P)
JERSEY CITY, NJ	1880-1981	1896-1981	
NEWARK, NJ	1880-1981	1896-1981	
PLAINFIELD, NJ	1880-1981	1896-1981	
BOONTON, NJ	1885-1981	1896-1981	1880-1884 (P)
CHARLOTTEBURG, NJ	1885-1981	1896-1981	1880-1884 (P)
SCARSDALE, NY	1880-1981	1890-1892 1904-1981	1893-1903 (A)
NEW YORK, NY	1880-1981	1890-1981	
WEST POINT, NY	1880-1981	1890-1981	
ALBANY, NY	1880-1981	1890-1981	
MOHONK LAKE, NY	1880-1981	1896-1981	
LITTLE FALLS, NY	1897-1981	1900-1981	1880-1886 (P) 1896-1899 (A)
SCHENECTADY, NY	1880-1981	1890-1981	
SLIDE MT., NY	1947-1981	1961-1981	1880-1946 (P) 1896-1960 (A)
GLOVERSVILLE, NY	1880-1888 1892-1981	1897-1981	1889-1891 (P) 1896 (A)
TRENTON FALLS, NY	1880-1981	1890-1904 1912-1917 1927-1981	1905-1911 (A) 1918-1926 (A)
SMITH BASIN, NY	1880-1981	1931-1981	1896-1930 (A)
INDIAN LAKE, NY	1899-1981	1900-1981	1880-1898 (P) 1896-1899 (A)

regions between the estuaries. These locations, spanning the region from Nantucket to Cape Hatteras, were:

- Nantucket, Massachusetts -- a region north of the Narragansett Bay and Hudson/Raritan estuaries but accessible to offshore spawning stocks caught in the target areas

- Block Island, Rhode Island -- a region adjacent to the mouth of Narragansett Bay

- New Haven, Connecticut -- a region adjacent to the mouth of the Connecticut River

- New York, New York -- a region directly adjacent to the mouth of the Hudson/Raritan estuary

- Atlantic City, New Jersey -- a region characterizing the coastal shore between the Hudson/Raritan estuary and the Delaware Bay, which is used as a spawning area by stocks from both target locations

- Cape May, New Jersey -- a region directly adjacent to the mouth of the Delaware Bay

- Cape Henry, Virginia -- a region directly adjacent to the mouth of the Chesapeake Bay

- Cape Hatteras, North Carolina -- a region directly south of Chesapeake Bay but accessible to offshore spawning stocks caught in target areas.

Data on wind speed and direction for the period 1889-1980 were hand transcribed from original daily data sheets and monthly summaries supplied by the National Climate Center. The data were keypunched into computer-compatible form and entered into the Martin Marietta/NOAA database. The stations and years for which wind data are available are listed in Table 8. This data-collection effort encompassed about 19,200 individual data records which were used to construct 96 monthly time series of wind speed and direction for the period 1889-1980.

3.1.3 Environmental and water quality data

For each target estuarine watershed, stations from which to collect data on freshwater discharge were selected from station location maps and record period lists provided by the United States Geological Survey in Reston, VA. The stations selected and their periods of record are listed in Table 9. Daily discharge records were received from the National Water Data Exchange (NAWDEX) for all requested stations and for periods ranging from 87 years (Point of Rocks, MD) to 3 years (Pine Brook, NJ).

Attempts to gather missing discharge data proved fruitless. All additions to the discharge data set were obtained by rectification and statistical modeling. These methods are more fully described in Section 4.

All discharge data were entered into the Martin Marietta/NOAA database. This data collection effort produced 700,800 individual records, which were

Table 8. Stations and years for which wind data are available

Station	Record Length
Cape May, NJ	1897-1980
Cape Henry, VA	1893-1981
New Haven, CT	1893-1980
Atlantic City, NJ	1893-1958
New York, NY	1893-1981
Nantucket, MA	1893-1968
Block Island, RI	1889-1950
Hatteras, NC	1893-1980

Table 9. Periods for which daily data on freshwater discharge are available from each station

Estuary and Station Location	Period Data Available
POTOMAC RIVER	
CUMBERLAND, MARYLAND	10/01/29-9/30/82
HANCOCK, MARYLAND	10/01/32-9/30/82
POINT OF ROCKS, MARYLAND	02/01/95-9/30/82
LITTLE FALLS, MARYLAND	03/01/30-9/30/82
HUDSON RIVER/RARITAN RIVER (AND TRIBUTARIES)	
(HACKENSACK RIVER) NEW MILFORD, NEW JERSEY	10/01/21-9/30/82
(PASSAIC RIVER)	
MILLINGTON, NEW JERSEY	12/01/03-9/30/82
CHATHAM, NEW JERSEY	03/01/03-9/30/82
PINE BROOK, NEW JERSEY	10/01/79-9/30/82
(PEQUANNOCK RIVER)	
MACOPIN DAM, NEW JERSEY	10/01/22-9/30/82
(RAMAPO RIVER)	
MAHWAH, NEW JERSEY	10/01/02-9/30/82
POMPTON LAKES, NEW JERSEY	10/01/21-9/30/82
(POMPTON RIVER)	
POMPTON PLAINS, NEW JERSEY	10/01/03-9/30/82
(RAHWAY RIVER)	
RAHWAY, NEW JERSEY	10/01/21-9/30/82
(RARITAN RIVER)	
RARITAN, NEW JERSEY	10/01/23-9/30/82
MANVILLE, NEW JERSEY	10/01/03-9/30/82
BOUND BROOK, NEW JERSEY	09/01/03-9/30/82
CALCO DAM, NEW JERSEY	09/01/03-9/30/82
(MILLSTONE RIVER)	
PRINCETON, NEW JERSEY	6/17/72-9/30/82
BLACKWELLS MILLS, NEW JERSEY	10/01/21-9/30/82
(LAWRENCE BROOK)	
FARRINGTON DAM, NEW JERSEY	05/01/27-9/30/82
(SOUTH RIVER)	
OLD BRIDGE, NEW JERSEY	08/01/39-9/30/82

Table 9. (continued)

Estuary and Station Location	Period Data Available
HUDSON RIVER/RARITAN RIVER (AND TRIBUTARIES) (CONTINUED)	
(MOHAWK RIVER)	
LITTLE FALLS, NEW YORK	10/01/01-9/30/82
LITTLE FALLS, NEW YORK	10/01/27-9/30/82
CRESCENT DAM, NEW YORK	10/01/60-9/30/82
(HUDSON RIVER)	
TROY, NEW YORK	10/01/08-9/30/82
CONNECTICUT RIVER	
THOMPSONVILLE, CONNECTICUT	10/01/72-9/30/82
NARRAGANSETT BAY TRIBUTARIES	
(TAUNTON RIVER)	
BRIDGEWATER, MASSACHUSETTS	10/01/29-9/30/82
(BRANCH RIVER)	
FORESTDALE, RHODE ISLAND	1/17/40-9/30/82
(BLACKSTONE RIVER)	
WOONSOCKET, RHODE ISLAND	2/17/29-9/30/82
(PAWTUXET RIVER)	
CRANSTON, RHODE ISLAND	12/01/39-9/30/82
DELAWARE RIVER	
RIEGELSVILLE, NEW JERSEY	07/01/06-9/30/82
TRENTON, NEW JERSEY	10/01/12-9/30/82

used to construct 32 annual, 128 seasonal, and 384 monthly time series for the period 1920-1980.

Stations from which to collect water quality data were selected from printouts (supplied by NAWDEX) that showed the starting and ending points of data collection (not necessarily continuous), but did not show which water quality variables were measured. The STORET database was searched for the 350 stations selected within the target watersheds and the 150 water quality variables to obtain recent data on water quality. Long-term time series of water quality data are not readily available from STORET and were constructed as described in Section 2. Table 10 lists the water quality variables on which data were collected. This data-collection effort produced 9,585 individual records.

3.2 Description of Fisheries/Climate Database

The database for the Historical Fisheries/Pollution Program is a Statistical Analysis System (SAS) database composed of 45 SAS libraries; these libraries are documented in the Appendix, parts 1-8. Nineteen of the libraries contain fisheries data by estuary or state, and the remainder are specific libraries for data on environmental and pollution variables.

The fisheries libraries that contain raw data are:

- RC.NOAA.SAS.POTOMAC.DAT
- RC.NOAA.SAS.DELAWARE.DAT
- RC.NOAA.SAS.HUDSON.DAT
- RC.NOAA.SAS.CONNETIC.DAT
- RC.NOAA.SAS.NARRAGAN.DAT
- RC.NOAA.SAS.STATE.MARYLAND.DAT
- RC.NOAA.SAS.STATE.DELAWARE.DAT
- RC.NOAA.SAS.STATE.NEWJERSY.DAT
- RC.NOAA.SAS.STATE.NEWYORK.DAT
- RC.NOAA.SAS.STATE.CONNETIC.DAT
- RC.NOAA.SAS.STATE.RHODEISL.DAT
- RC.NOAA.SAS.STATE.VIRGINIA.DAT
- RC.NOAA.SAS.STATE.PENNSYLV.DAT.

Each raw-data library, as appropriate, contains four SAS data sets:

- BIOLOGY -- landings data for all fisheries

Table 10. Water quality variables on which data were collected from EPA-STORET database

PHYSICAL VARIABLES	NUTRIENTS	METALS	ORGANICS
WATER TEMPERATURE (°C)	RESIDUE DISSOLVED 105°C (mg/L)	CALCIUM DISSOLVED (mg/L)	DDD WHOLE SAMPLE (µg/L)
TURBIDITY (JTU)	NO_3 TO N DISSOLVED (mg/L)	MAGNESIUM DISSOLVED (mg/L)	DDD MUD (µg/L)
TURBIDITY (JCU)	NO_3 TO N TOTAL (mg/L)	SODIUM DISSOLVED (mg/L)	DDE WHOLE SAMPLE (µg/L)
TURB (FTU)	NO_2- AND NO_3-N DISSOLVED (mg/L)	POTASSIUM DISSOLVED (mg/L)	DDE MUD (µ/KG)
CONDUCTIVITY AT 25 °C (µMHO)	TOTAL PO4 PO4 (mg/L)	CHLORIDE TOTAL (mg/L)	DDT WHOLE SAMPLE (µg/L)
TIME OF TRAVEL (HOURS)	ORTHOPHOSPHATE PO_4 (mg/L)	SULFATE TOTAL (µg/L)	DDT MUD (µg/KG)
DISSOLVED OXYGEN (mg/L)	PHOSPHORUS TOTAL (mg/L)	ARSENIC TOTAL (µg/L)	DIELDRIN TOTAL (µg/L)
BIOLOGICAL OXYGEN DEMAND, 5-DAY (mg/L)	TOTAL ORGANIC CARBON (mg/L)	BARIUM DISSOLVED (µg/L)	DIELDRIN SEDIMENT (µg/KG DRY WT)
CHEMICAL OXYGEN DEMAND, HI LEVEL (mg/L)	DISSOLVED ORGANIC CARBON (mg/L)	CADMIUM TOTAL (µg/L)	DIELDRIN SHELLFISH (µg/KG DRY WT)
pH (SU)	SUSPENDED ORGANIC CARBON (mg/L)	CHROMIUM TOTAL (µg/L)	ENDOSULN WHOLE SAMPLE (µg/L)
TOTAL ALKALINITY $CaCO_3$ (mg/L)	DISSOLVED SOLIDS SUM (mg/L)	COBALT DISSOLVED (µg/L)	ENDOSULN MUD (µg/KG)
SALINITY (PARTS/1,000)	DISSOLVED SOLIDS (TONS/DAY)	COPPER TOTAL (µg/L)	ENDRIN TOTAL (µg/L)
TOTAL HARDNESS $CaCO_3$ (mg/L)	DISSOLVED SOLIDS (TONS PER ACRE-FT)	IRON TOTAL (µg/L)	ENDRIN SEDIMENT (µg/L DRY WT)
TOTAL ACIDITY AS H (mg/L)	SESTON TOTAL (mg/L)	LEAD TOTAL (µg/L)	ETHION WHOLE SAMPLE (µg/L)
SUSPENDED SEDIMENT CONCENTRATION (mg/L)	SESTON ASH WT (mg/L)	MANGANESE (µ/L)	ETHION MUD (µg/KG)
SUSPENDED SEDIMENT DISCHARGE (TONS/DAY)	NITRATE TOTAL NO_3 (mg/L)	MOLYBDENUM DISSOLVED (µg/L)	TOXAPHENE TOTAL (µg/L)
BED MATERIAL PARTICLE SIZE (%<0.004 mm)	NITRATE DISSOLVED NO_3 (mg/L)	NICKEL DISSOLVED (µg/L)	TOXAPHENE SEDIMENT (µg/KG DRY WT)
BED MATERIAL PARTICLE SIZE (%<0.062 mm)	TOTAL P AS PO_4 (mg/L)	SILVER DISSOLVED (µg/L)	DIELDRIN TISSUE (µg/KG WET WT)
BED MATERIAL PARTICLE SIZE (%<2.00 mm)	TOTAL N AS NO_3 (mg/L)	ZINC TOTAL (µg/L)	HEPTACHLOR TOTAL (µg/L)
TOTAL SEDIMENT PARTICLE SIZE (%<1.00 mm)		SELENIUM DISSOLVED (µg/L)	HEPTACHLOR SEDIMENT (µg/KG DRY WT)
		MERCURY DISSOLVED (µg/L)	HEPCHLREP TOTAL (µg/L)
		MERCURY TOTAL (µg/L)	HEPCHLREP SEDIMENT (µg/KG DRY WT)
			METHXYCHLOR WHOLE SAMPLE (µg/L)
BACTERIA	OTHER		METHXYCHLOR MUD DRY (µ/KG)
			METHOXYCHLOR FISH (µg/KG)
FECAL COLIFORM (MFNECMED) (/100 ml)	DEAD FISH (SEVERITY)		PCB 1221 TOTAL (µg/L)
FECAL COLIFORM (MFM FCBR) (/100 ml)			PCB 1221 SEDIMENT (µg/KG DRY WT)
			PCB 1232 TOTAL (µg/L)
			PCB 1232 SEDIMENT (µ/KG DRY WT)

Table 10. (continued)

ORGANICS	ORGANICS	ORGANICS
PCB 1242 TOTAL (µg/L)	MALATHION WHOLE SAMPLE (µg/L)	2, 4-D WHOLE SAMPLE (µg/L)
PCB 1242 SEDIMENT (µg/KG DRY WT)	MALATHION MUD (µg/KG)	2, 4-D MUD (µg/KG)
PCB 1243 TOTAL (µg/L)	PARATHION WHOLE SAMPLE (µg/L)	2, 4-D FILTERED FRACTION (µg/L)
PCB 1248 SEDIMENT (µg/KG DRY WT)	PARATHION MUD (µ/KG)	2, 4, 5-T WHOLE SAMPLE (µg/L)
PCB 1254 TOTAL (µg/L)	DIAZINON WHOLE SAMPLE (µg/L)	2, 4, 5-T MUD (µ g/KG)
PCB 1254 SEDIMENT (µg/KG DRY WT)	DIAZINON MUD (µg/KG)	2, 4, 5 T-FILTERED FRACTION (µg/L)
PCB 1260 TOTAL (µg/L)	M-PARATHION WHOLE SAMPLE (µg/L)	MIREX WHOLE SAMPLE (µg/L)
PCB 1260 SEDIMENT (µg/KG DRY WT)	M-PARATHION MUD (µg/KG)	MIREX BOTTOM MATERIAL (µg/KG)
PCB 1254 FISH TISSUE (µg/KG)	ATRAZINE WHOLE SAMPLE (µg/L)	SILVEX WHOLE SAMPLE (µg/L)
PCB 1016 SEDIMENT (µg/KG DRY WT)	ATRAZINE MUD (µg/KG)	SILVEX MUD (µg/KG)
PCBS WHOLE SAMPLE (µg/L)	HYDROCHLOROBENZENE TOTAL (µg/L)	SILVEX FILTERED FRACTION (µg/L)
PCBS FILTERED FRACTION (µg/L)	HYDROCHLOROBENZENE SEDIMENT (µg/KG DRY WT)	LINDANE WHOLE SAMPLE (µg/L)
PCBS MUD (µg/KG)	HEXACHLOROBENZODIOXIN TOTAL (µg/L)	LINDANE MUD DRY (µg/KG)
PCBS SHELLFISH (µg/KG DRY WT)	HYDROCHLOROBENZENE FISH WET WEIGHT (µg/KG)	TRITHION WHOLE SAMPLE (µg/L)
		TRITHION MUD (µg/KG)
		M-TRITHION WHOLE SAMPLE (µg/L)
		M-TRITHION MUD (µg/KG)

- BIOGEAR -- catch-by-gear data for all fishery-gear combinations
- COST -- cost-per-pound data for all fisheries
- EFFORT -- fishing effort data for all gears.

The fish stock libraries are estuarine specific and are composed of catch-per-unit-effort-like time series (described fully in Section 4). The six stock libraries are:

- RC.NOAA.SAS.POTOMAC.STOCK.DAT
- RC.NOAA.DELAWARE.STOCK.DAT
- RC.NOAA.HUDSON.STOCK.TMP
- RC.NOAA.CONN.STOCK.DAT
- RC.NOAA.NARR.STOCK.DAT
- RC.NOAA.COASTAL.STOCK.DAT.

Each stock library contains multiple (10-30) SAS data sets corresponding to the stocks located in the estuary or region (e.g., striped bass, shad, alewife).

The climate and wind libraries that contain raw data are:

- RC.NOAA.SAS.CLIMATE.DAT
- RC.NOAA.SAS.WIND.DAT.

Each of these libraries represents a massive single data set with information keyed to individual climate stations.

The freshwater flow library is:

- RC.NOAA.SAS.USGS.FLOW.DAT.

This library contains six SAS data sets:

- AGENCY -- agency that collected data
- STATION -- station locations
- STNAME -- station location descriptions
- CODE -- codes
- FLOW -- flow data
- BASEDIS -- baseline discharge data.

The hydrographic libraries associated with specific analyses for target stock-estuary combinations are rectified series (see Section 4). The 10 hydrographic libraries are:

- RC.NOAA.SAS.POTOMAC.CLIMATE.DAT
- RC.NOAA.SAS.HUDSON.WORK2.DAT
- RC.NOAA.SAS.DELAWARE.CLIMATE.DAT
- RC.NOAA.SAS.NARRAGAN.CLIMATE.DAT
- RC.NOAA.SAS.CONNECT.CLIMATE.DAT
- RC.NOAA.POTOMAC.CLIMATE.DAT
- RC.NOAA.HUDSON.CLIMATE.DAT
- RC.NOAA.DELAWARE.CLIMATE.DAT
- RC.NOAA.NARRAGAN.CLIMATE.DAT
- RC.NOAA.CONNECT.CLIMATE.DAT.

The RC.NOAA.SAS.* libraries contain the rectified time series of data on climate, wind, and freshwater flow at each estuarine station and represent all independent hydrographic variables used in the analyses for each estuary. The remaining libraries contain the specific time series used in each analysis for each stock-location combination. Each of these libraries contains multiple data sets corresponding to the stocks analyzed in a specific estuary (e.g., CLIMBASS, CLIMSHAD, CLIMALE).

4. ANALYTICAL METHODS

A variety of methods are used to develop, rectify, or analyze the fisheries data for the historical fisheries program. These methods include (defined below) stock time-series development, development of time-series analytical methods, and time-series rectification. Stock time-series development refers to the analysis of data on local and regional fisheries to develop a "relative measure of fishable stock" time series for the target estuaries (e.g., a stock measure for the Potomac River was developed from data on Potomac landings, Maryland and Virginia landings, Maryland and Virginia fishing effort, and Maryland and Virginia catch by gear). Development of time-series analytical methods refers to Martin Marietta Environmental Systems' tailoring of categorical regression for application to fisheries problems and time-series analysis. Time-series rectification refers to filling in data missing from a time series, and it can take several alternative forms depending on the specific data missing from the individual series. Rectification can refer to 1) modeling existing time-series data either to fill in a few data points missing from within an otherwise adequate long-term record, or 2) extending the time series to cover previous periods for which no data are available.

4.1 Relative Stock Measures

Depending upon the degree to which fishing effort affects landings, commercial landings may or may not be a measure of stock abundance. The Martin Marietta Environmental Systems/NOAA database contains specific landings records for each estuary, but no long-term data sets on estuary-specific fishing effort were available. In contrast, data were available on state-specific landings, licensed effort, and catch by gear. The analytical task was, therefore, to use the available data to develop an estuary-specific stock measure indicating abundance in each target estuary. Such a measure can be computed by use of probability theory, provided a few assumptions are reasonably acceptable, and stock abundance is related to landings by effort.

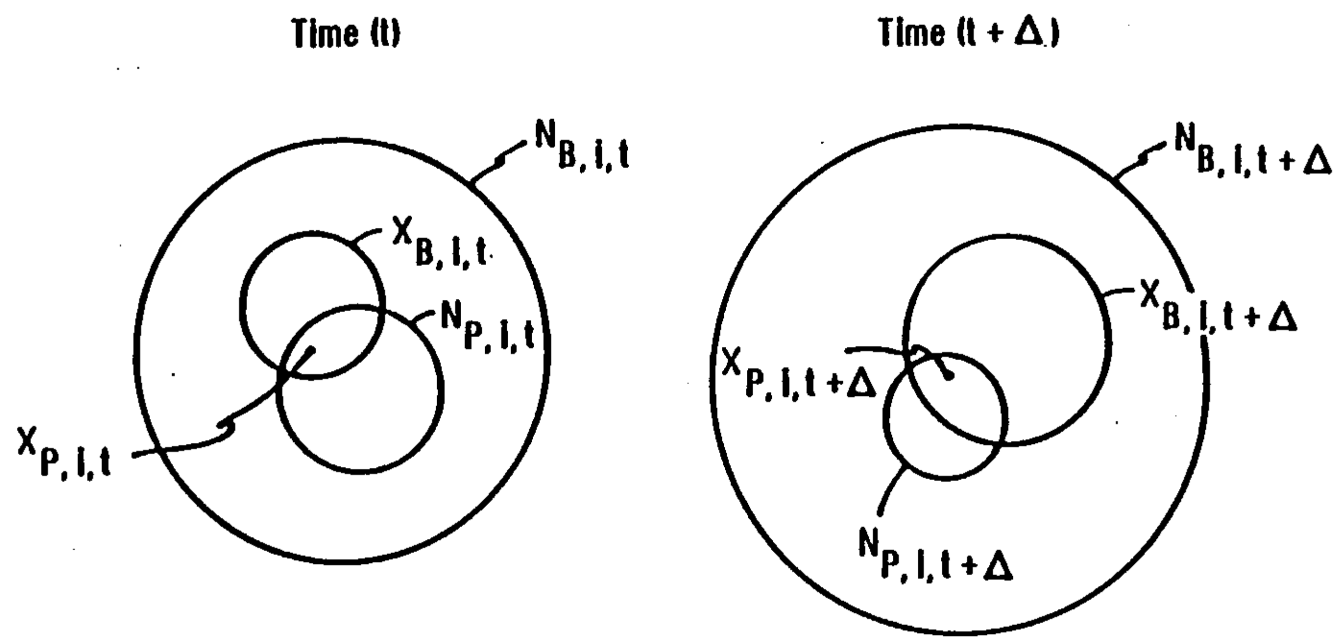
Theoretically, the relationship between local and regional stocks and commercial landings can be depicted as Venn diagrams (Fig. 33). At some time (t), the stock size (N) of some locale (P) of some species (i) is $N_{P,i,t}$, a subset of the stock size of some region (B), which is $N_{B,i,t}$. The regional commercial catch of species i is $X_{B,i,t}$, and the local commercial catch of species i is $X_{P,i,t}$, represented on the Venn diagram as the area of intersection between $N_{P,i,t}$ and $X_{B,i,t}$. While the magnitudes of these variables may change with time (i.e., Fig. 33 at t + Δ), their basic relationship remains intact.

The probability (Pr) that a fish will be caught (C) and will be in the local stock is $(X_{P,i,t}|N_{B,i,t})$, which is equivalent to:

$$\Pr \text{ (being caught} | \text{being in local stock)} \cdot \Pr \text{ (being in local stock)}$$

or

$$\Pr (C|P) \cdot \Pr (P|B)$$



$N_{B,i,t}$ = total stock for species i (region includes local)

$N_{P,i,t}$ = local stock for species i

$X_{B,i,t}$ = total catch for species i (region includes local)

$X_{P,i,t}$ = local catch for species i

Figure 33. Venn diagram of relationships between local and regional stock abundance and commercial landings.

which can be determined by substitution as:

$$\frac{X_{P,i,t}}{N_{B,i,t}} = Pr\ (C|P) \cdot \frac{N_{P,i,t}}{N_{B,i,t}}$$

which reduces to:

$$N_{P,i,t} = \frac{X_{P,i,t}}{Pr\ (C|P)}.$$

If we define a constant, α_i, such that:

$$\alpha_i = \frac{Pr\ (C|P)}{Pr\ (C)}$$

then, by substitution:

$$N_{P,i,t} = \frac{X_{P,i,t}}{\alpha_i \cdot Pr\ (C)} = \frac{X_{P,i,t} \cdot N_{B,i,t}}{\alpha_i \cdot X_{B,i,t}}.$$

If we further assume, as indicated by classical fisheries science (Ricker, 1975), that stock abundance is related to commercial landings by effort (E) and catchability (q), then:

$$N_{B,i,t} = \frac{X_{B,i,t,k}}{q_{B,i,t,k} \cdot E_{B,i,t,k}}.$$

where

$E_{B,i,t,k}$ = effort in region B for species i at time t associated with gear k

$q_{B,i,t,k}$ = catchability in region B for species i at time t associated with gear k.

Then, by substitution:

$$N_{P,i,t} = \frac{X_{P,i,t}}{X_{Bi,t}} \cdot \frac{X_{B,i,t,k}}{\alpha_i \cdot E_{B,i,t,k}}$$

If α_i is assumed to be time-invariant (i.e., constant), then:

$$\alpha_i = \frac{(q_{P,i,t,k})(E_{P,i,t,k})}{(q_{B,i,t,k})(E_{B,i,t,k})}$$

and

$$N_{P,i,t} = \frac{X_{P,i,t}}{X_{B,i,t}} \cdot \frac{X_{B,i,t,k}}{E_{B,i,t,k}} .$$

Thus, local relative abundance of fishable stock can be determined from regional and local landings, regional catch by gear, and regional effort if classical fisheries assumptions and the proposed time invariance of α_i are acceptable. The major point of decision in this estimate then becomes the determination of which gear to use in the calculation. In general, we used the gear that accounts for the greatest percentage of the regional landings (i.e., $X_{B,i,t,k}/X_{B,i,t}$ is the largest).

For example, the Potomac fishery is a subset of the Chesapeake Bay fishery, which is a composite of the Maryland and Virginia state fisheries. With our approach, we can determine, for instance, the relative stock abundance of Potomac striped bass from time series of commercial catch of striped bass in the Potomac River, commercial catch in Maryland and Virginia, catch by the gear accounting for the greatest proportion of catch in Maryland and Virginia, and commercial effort in Maryland and Virginia for that gear. The primary gear used for striped bass harvest is the gill net, regardless of the specific type. Relative stock abundance of Potomac River striped bass can thus be determined as:

$$S_P = \frac{C_P}{C_B} \cdot \frac{C_B^K}{E_B^K}$$

where

S_P = relative stock abundance for striped bass in the Potomac River

C_P = commercial catch of striped bass in the Potomac River

C_B = commercial catch of striped bass in Chesapeake Bay

C_B^K = commercial catch of striped bass by gill net in Chesapeake Bay

E_B^K = total yardage of gill nets licensed in Chesapeake Bay.

This method results in a catch-per-unit-effort-like time series of adjusted landings for Potomac River striped bass, with the gross effects of variation in effort removed (i.e., a relative stock measure, Fig. 34). Application of regression analyses to the question of how these Potomac River landings and the juvenile index values for striped bass (Boone, 1956-1980) are related to

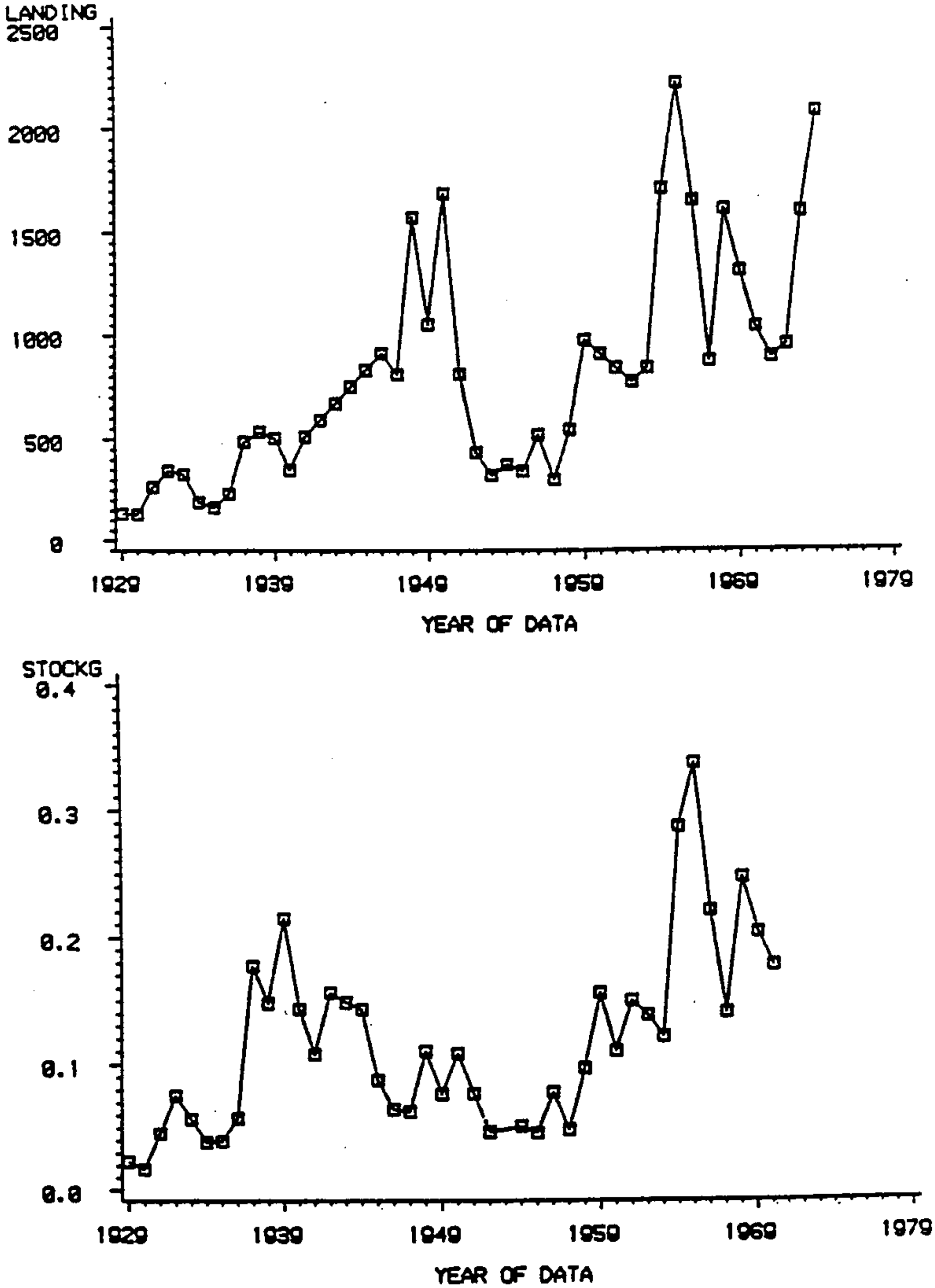


Figure 34. Commercial catch (in thousands of pounds) and modeled relative stock size (in catch per unit effort) for striped bass in the Potomac River, 1929-1976.

the relative stock and juvenile indices revealed that the relationship between stock index and juvenile index is stronger than the relationship between landings and juvenile index (R^2 values of 0.84 and 0.63, respectively). We have developed relative-stock time series for all target species in the five estuaries.

4.2 Data Rectification

Data rectification for climatic data (air temperature, precipitation, and freshwater discharge) took two basic forms: the missing data were either interpolated by use of periodic regressions or modeled by use of time-series regression techniques.

The air temperature and precipitation data received from the National Climate Center for the target watersheds were nearly complete. Of the 1,044 monthly values used to construct each time series for air temperature or precipitation at each station location, only about 10-50 data points were missing. Usually, no more than 2-3 consecutive points were absent from a time-series record.

The climate time series for all the target basins were rectified by use of simple periodic regression, in which climate was described as a function of season. For example, in estimating the 41 missing values from the time series for air temperature at Solomons, MD, air temperature (A) at time (t) was modeled as:

$$\begin{aligned} A_T = B_0 &+ B_1 \cos(\omega_1 \times t) + B_2 \sin(\omega_1 \times t) + \\ &B_3 \cos(\omega_2 \times t) + B_4 \sin(\omega_2 \times t) + \\ &B_5 \cos(\omega_3 \times t) + B_6 \sin(\omega_3 \times t) + \\ &B_7 \cos(\omega_4 \times t) + B_8 \sin(\omega_4 \times t) + \varepsilon \end{aligned}$$

where

$$\omega_1 = 2\Pi/12$$

$$\omega_2 = 2\Pi/6$$

$$\omega_3 = 2\Pi/4$$

$$\omega_4 = 2\Pi/3.$$

The values for the seasonal coefficients (B_i) resulting from interpolation of temperature data for Solomons are listed in Table 11. The R^2 value for the fit is 0.96. Figure 35 shows both the original time series and the completed time series with the interpolated values for this example. All air temperature records were rectified in this manner.

Execution of the planned analyses requires complete (1880-1980) time series on freshwater discharge at or near the fall line for each target estuary. Since the available data on freshwater discharge into the estuarine

Table 11. Seasonal coefficients from interpolation of data on air temperature at Solomons, Maryland

Coefficient	Value
B_0	57.60
B_1	-16.79
B_2	-13.13
B_3	-0.61
B_4	-0.12
B_5	+0.01
B_6	+0.11
B_7	-0.01
B_8	-0.17

$R^2 = 0.96$

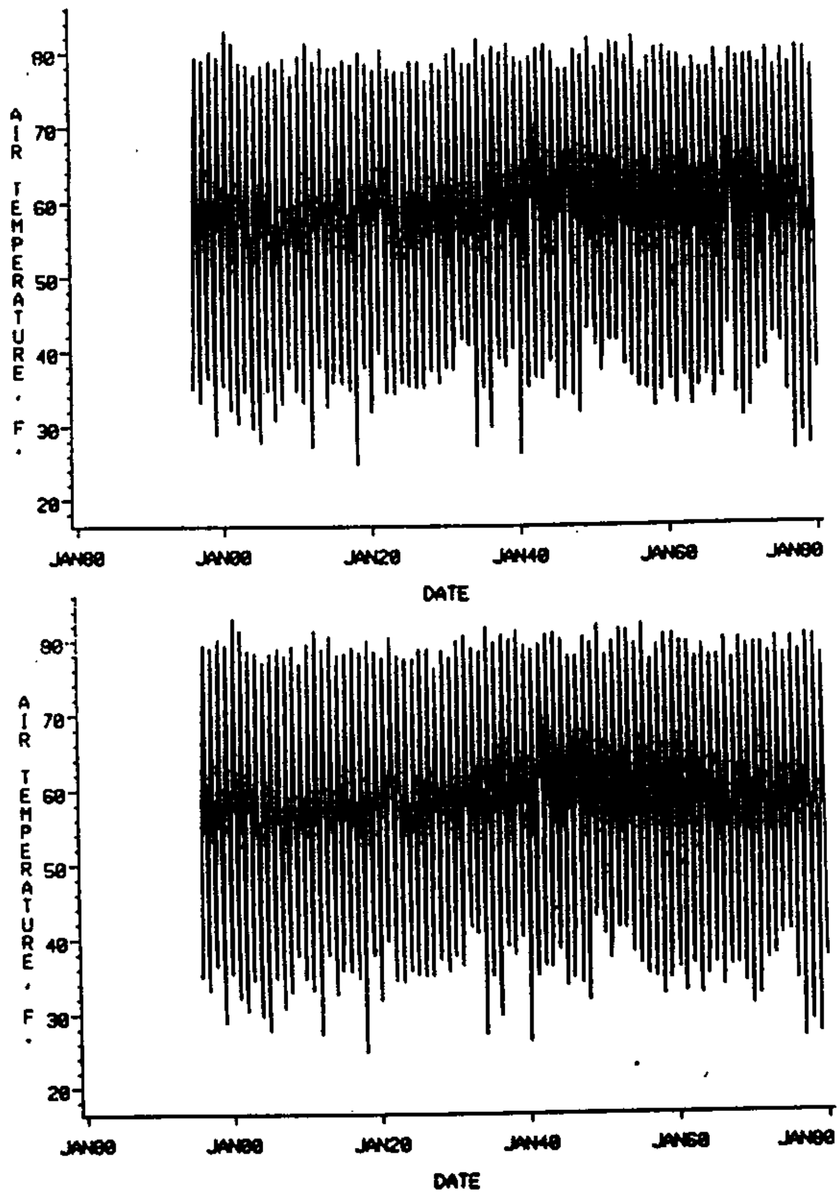


Figure 35. Air temperature at Solomons, Maryland, plotted before (top) and after (bottom) interpolation of missing values.

portion of target estuaries generally begin in 1930 (Fig. 36, top right), modeling rectification was used to estimate data for the period 1880-1929.

Missing data generally were reconstructed by a two-step statistical modeling process. For example, in modeling the flow for the Potomac River at Little Falls, MD, the flow for the period 1895-1930 and the flow for the period 1880-1895 were reconstructed separately. The reconstruction process was divided in this way because the availability of concurrent data on upstream flow and climate for 1895-1930 allowed straight-forward analyses; alternative analytical procedures had to be used for the period 1880-1895. The data applied to the period 1895-1930 were:

- The flow observed at Point of Rocks, MD, for the period 1895-1980 (Fig. 36, top right). This station is about 50 miles upstream of the fall line, and one tributary -- the Monocacy River -- joins the Potomac River between the station and the fall line.

- The observed precipitation at Great Falls, MD (Fig. 36, bottom left), which indicates the input of runoff associated with the region between Point of Rocks and Great Falls.

The flow at Little Falls was modeled as an autoregressive process of flow at Point of Rocks and of total precipitation at Great Falls. The model was constructed as:

$$Y' = B_0 + B_1 X_1' + B_2 X_2' + \varepsilon$$

where

$$Y' = Y_t - P_1 Y_{t-1} = \text{corrected flow at Little Falls}$$

$$X_1' = X_{1,t} - P_1 X_{1,t-1} = \text{corrected flow at Point of Rocks}$$

$$X_2' = X_{2,t} - P_1 X_{2,t-1} = \text{corrected precipitation at Great Falls}$$

and

$$Y_t = \text{observed flow at Little Falls at time } t$$

$$X_{1,t} = \text{observed flow at Point of Rocks at time } t$$

$$X_{2,t} = \text{observed precipitation at Great Falls at time } t$$

$$\varepsilon = \text{residual error.}$$

The term P_1 (where time lag i = 1) represents the autocorrelation of the residuals from an ordinary least-squares regression performed with the above variables. The observations were corrected for serial correlation among the residuals by use of the Cochrane-Orcutt transformation (Cochrane and Orcutt, 1949; Judge et al., 1980; Harvey, 1981).

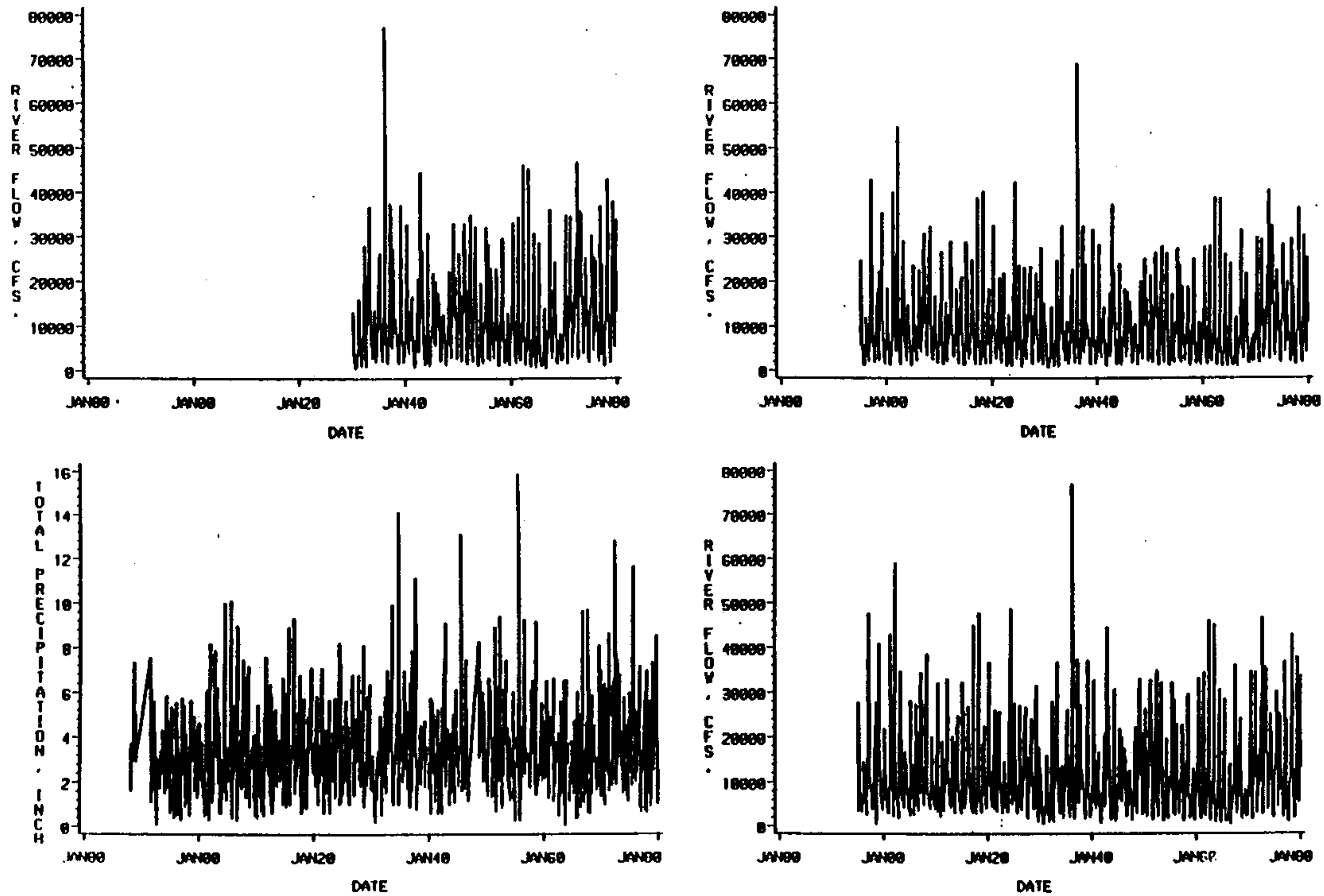


Figure 36. Results of modeling to extend time series of freshwater discharge data for Little Falls, MD, to cover the period 1895-1930; and data used in modeling: Top left, original (observed) data on flow at Little Falls; top right, flow at Point of Rocks, MD; bottom left, precipitation at Great Falls, MD; bottom right, extended time series of flow at Little Falls.

The estimation method used in autoregression is called the two-step full transform method (Harvey, 1981). First, estimates of the model $Y = BX + \mu$ are determined by use of ordinary least squares (OLS). Then, the autocovariances up to lag i of the residuals from the OLS regression are computed. The Yule-Walker equations (Gallant and Goebel, 1976) are solved to obtain estimates of the autoregressive parameters and a preliminary estimate of the variance. All the variables from the original data are then transformed: the first i observations by use of the Choleski root of the Yule-Walker equation, and the remaining observations by use of the autoregressive parameters. Finally, B is reestimated from the transformed data by an OLS regression. This method is somewhat similar to a generalized least-squares estimation procedure with appropriate weighting.

Application of this procedure to the data on observed flow at Little Falls permitted the reconstruction of freshwater discharge data back to 1895. The fitted model has an R^2 value of 0.997 and is represented as:

$$Y = -84.91 + 1.14\, X_1{}' + 136.13 X_2{}' + \varepsilon \, .$$

The observed and reconstructed flows at Little Falls are shown in Fig. 36 (top left and bottom right, respectively).

The final analytical task in flow reconstruction for Little Falls was to fill in the period from 1880 to 1895. No upstream flow data were available for years prior to 1895, but precipitation data for the period were available for upstream and downstream locations. Data on precipitation at Washington, DC (river mile 100), and Cumberland, MD (river mile 305) (Fig. 37, top left and top right, respectively), constituted good long-term records for these regions. Flow at Little Falls for the period 1880-1895 was modeled as the combination of an expected seasonal mean flow and a deseasonalized component based on local and regional (i.e., upstream) precipitation.

Pre-1895 flow was reconstructed in two phases. First, the seasonal component of the 1895-1980 data was removed, by use of periodic regression, to generate an expected seasonal pattern for flow at Little Falls. The process was identical to that used to fill in missing air temperature values, previously described. The results of this phase of the analysis are shown in Table 12; the seasonal component accounted for 33% of the variation in the time series on flow.

Next, the residuals from the first step (which can be termed deseasonalized flow) were modeled as a function of local and regional (upstream) precipitation. (Upstream rainfall is, in essence, a surrogate for upstream flow.) Autoregression was used for the modeling in the same way as for the 1895-1930 data. The regression of deseasonalized flow accounted cumulatively for 46% of the variation in the original time series (Table 13).

The reconstructed flow was then determined as the sum of the expected seasonal component and the modeled deseasonalized component. The result was a complete time series of flow at Little Falls for the period 1880-1980 (Fig. 37, bottom).

These types of analyses have been used to reconstruct, when necessary, all climatic variables for the target estuaries. At this point we have

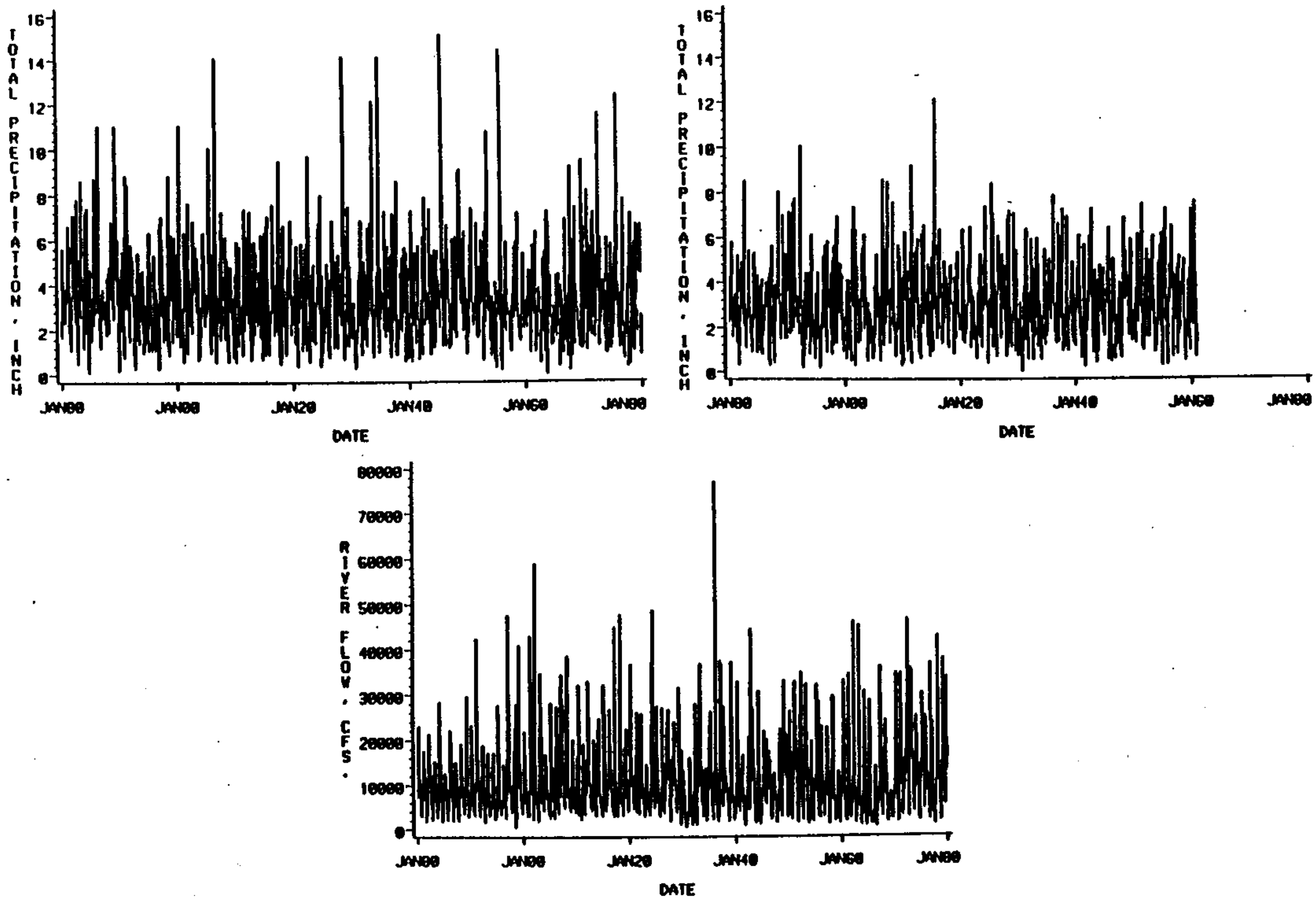


Figure 37. Results of modeling to extend time series of freshwater discharge data for Little Falls, MD, to cover the period 1880-1895; and precipitation data used in modeling: Top left, precipitation at Washington, D.C.; top right, precipitation at Cumberland, MD; bottom, extended time series of flow at Little Falls.

Table 12. Results of removing the seasonal component from the 1895-1980 data on freshwater discharge at Little Falls, Maryland

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- SEASONAL FLOW (1895-1982 MONTHLY SERIES)

$$F_S = 9.24 - 0.05 \cos(\omega_1 \tau) + 0.59 \sin(\omega_1 \tau)$$
$$- 0.07 \cos(\omega_2 \tau) - 0.06 \sin(\omega_2 \tau)$$
$$+ 0.02 \cos(\omega_3 \tau) - 0.02 \sin(\omega_3 \tau)$$
$$+ 0.04 \cos(\omega_4 \tau) - 0.00 \sin(\omega_4 \tau)$$
$$+ \xi$$

$R^2 = 0.33$

$\omega_1 = 2\pi/12$

$\omega_2 = 2\pi/6$

$\omega_3 = 2\pi/4$

$\omega_4 = 2\pi/3$

Table 13. Results of regression analysis of deseasonalized component of Little Falls flow

- DE-SEASONALIZED FLOW (TRANSFORMED FLOW MINUS SEASONAL FLOW) AS A FUNCTION OF LOCAL PRECIPITATION PLUS REGIONAL PRECIPITATION

$$F_{DS}' = -0.53 + 0.06\, P_1' + 0.12\, P_2' + \varepsilon$$

$$R^2 = 0.21$$

$$\text{CUM. } R^2 = 0.46$$

WHERE

$$F_{DS}' = F_{DS_T} - \rho_1 F_{DS_{T-1}} - P_2 F_{DS_{T-2}} \quad \text{(DESEASONALIZED FLOW)}$$

$$P_1' = P_1 - \rho_1 P_{1_{T-1}} - \rho_2 P_{1_{T-2}} \quad \text{(WASHINGTON, DC PRECIPITATION)}$$

$$P_2' = P_2 - \rho_1 P_{2_{T-1}} - \rho_2 P_{2_{T-2}} \quad \text{(CUMBERLAND, MD PRECIPITATION)}$$

- RECONSTRUCTED FLOW

$$\text{FLOW} = F_S + F_{DS}$$

constructed complete time series of air temperature, precipitation, wind speed and direction, and freshwater discharge for all target estuaries.

4.3 Categorical Time-Series Regression

Testing of hypotheses about the effects of pollution on stocks would be straightforward if information were available on specific stock-recruitment functional relationships, including the effects of pollutants on mortality. Unfortunately, an enormous amount of long-term information is needed for developing such relationships. Data would be required on stock history, age and sex structure, fecundity, mortality (natural and fishing), and recruitment, as well as on population-level responses to a whole host of common and exotic pollutants at all points in the life cycle. These kinds of data are unavailable for natural populations.

In lieu of such information, the most promising general approach for investigating the effects of pollutants was initially considered to be relationships of the type:

$$S(t) = B_0 + B_1 * S(t-r) + B_2 * (t-r-1) + \ldots\ldots + B_j * S(t-n) + \varepsilon$$

where

$S(t)$ = present value of stock index

r = minimum age of vulnerability to fishing

n = maximum age of vulnerability to fishing

B_j = regression coefficient

t = time

ε = residual error.

That is, the present value of stock size is assumed to depend in great part on contributions from all past fishable age groups. To test whether factors other than the past stock size contribute significantly to the variation in $S(t)$, we could hypothesize that the relationship

$$S(t) = B_0 + B_1 * S(t-r) * E(t-r) + \ldots\ldots + B_j * S(t-n) + \varepsilon$$

represents the compounded action of a suspected environmental variable E (climate and/or pollution) during the historical period that determines the present values of $S(t)$. Consideration of several extrinsic factors requires models of gradually increasing complexity.

Such a view of the problem is fraught with theoretical and practical difficulties. First, the model must include a specific hypothetical functional form for the inclusion of climatic and pollution terms, E. However, there is no _a priori_ reason for the inclusion of E as a multiplicative product: the dependence may be exponential for one climatic or pollution variate, and of yet a different form for another. Even more important, there is no basis for comparing gradually more complex models with simpler ones, since the functional forms of successive models are arbitrary and differ from each other mathematically. The situation quickly degenerates if a systematic testing procedure is desired, because such a procedure would require an enormous number of tests, with extrinsic factors in various combinations and forms.

The second major difficulty with this view of the hypothesis-testing process is purely statistical. As noted, the models contain time-lagged values of the dependent variable on the right-hand side. Ordinarily, when a time series is related to another independent time series, the form of transformations is adjusted to remove serially correlated errors. This procedure is tantamount to enabling the analysis to proceed according to the principles of ordinary least-squares estimation. There is no existing method for such an adjustment if the predictor variables are essentially the lagged predicted series, without inclusion of the one-step backward time lag (Johnston, 1972; Ostrom, 1978). If we were to proceed with the normal correction procedure in this case, the lack-of-model-fit error would become indistinguishable from errors in measuring the independent variables. In effect, the transformations would also remove periodic or lagged dependencies on the predictor variables (Rao and Miller, 1971). Thus, only nonsensical results are obtained from attempts to reduce the model formulation to a form suitable for valid application of the ordinary least-squares technique.

We therefore abandoned the linear, time-series model-building approach, and chose a method similar to indicator variable regression for analysis of the historical dependence of stock levels on their previous values and on other independent variables. The generalized method is also referred to as dummy variable or categorical variable regression; an introductory overview of the method is presented in Neter and Wasserman (1974).

4.3.1 Model structure

The first step in the analysis is to categorize the observations of the response variable and each of the explanatory variables' time series based on some criterion. For illustrative purposes, we use two categories (denoted 1 and 2), based on the median value of each time series. Use of the median is arbitrary and provided there are sufficient data, any number of categories can be defined based on a variety of possible critera. Breiman et al. (1984) provide an excellent discussion on alternative criteria for categorizing the explanatory variables, which in their nomenclature, are termed "splitting rules." A schematic representation of the categorical time-series regression approach is shown in Figure 38.

Using t to denote time, assume we have the original response variable (Y_t), the categorized response variable time series (X_{it}, i=1, n-1). We define a new variable (V_i), corresponding to each X_{it}, such that V_i equals the values assigned to the categories of X_{it} (i.e., for two categories, if X_{it}=1 or 2, then V_i=1 or 2). Treating the categorized response variable as the n^{th}

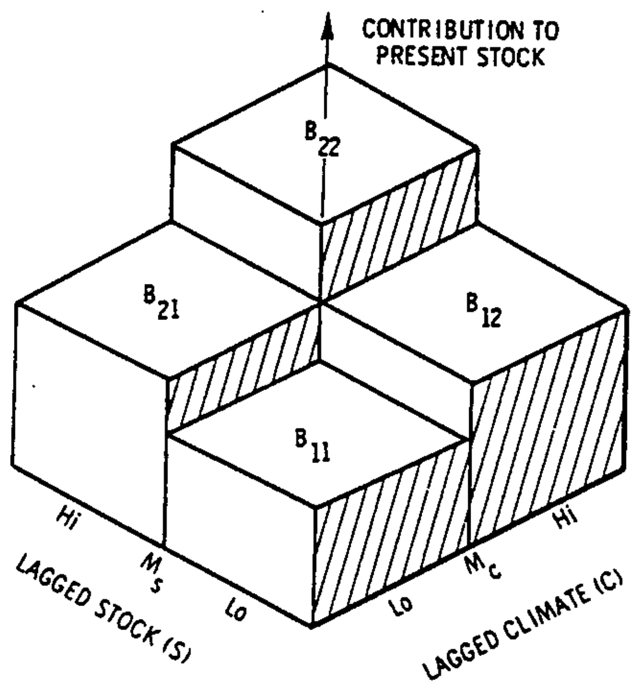

Figure 38. Schematic representation of a categorical time-series regression. Key: B_{11} to B_{22} represent contributions to present stock; M_i represents the median of variable i.

explanatory variable (i.e., X_{it}, i=1,n where $X_{nt}=Z_t$), the regression model is of the form:

$$Y_t = \sum_{m=q}^{p} \sum_{V_1=1}^{2} \sum_{V_2=1}^{2} \cdots \sum_{V_n=1}^{2} \left(B_{V_1,V_2,\ldots,V_n} \cdot W_{t-m,V_1,V_2,\ldots,V_n} + e_{V_1,V_2,\ldots,V_n} \right) \qquad (1)$$

where:

$$W_{t-m,V_1,V_2,\ldots,V_n} = \begin{cases} 1/(p-q+1) & \text{if } X_{1,t-m}=V_1 \\ & \text{and } X_{2,t-m}=V_2, \\ & \quad\vdots \\ & \text{and } X_{n,t-m}=V_n \\ o & \text{otherwise} \end{cases}$$

$B_{V_1,V_2,\ldots,V_n}$ = regression coefficients

$e_{V_1,V_2,\ldots,V_n}$ = errors

p = earliest (or farthest back in time) lag in the model

q = latest (or most recent) lag in the model.

In the case of two categories, the method involves defining 2^n cells, which cover all possible combinations of the categorized explanatory variables (i.e., values of each variable can either be high or low). Using this method we look back in time, within the window of time defined by the earliest and latest lags, at the levels of the categorized explanatory variables. The number of times that the conditions defined by each cell occur in the lagged observations corresponding to a given time t (i.e., between times t-p and t-q) is calculated. These are then divided by the number of lags in the model (p-q+1). For a total of T observations (i.e., t=1,2,...,T), the result is a T x 2^n design matrix in which each row represents a value of time and each column is associated with a cell. Each element of the matrix is the number of occurrences of those categories of explanatory variables defined by the cell, divided by the number of lags, which were observed in the lagged data associated with time t. The original response variable time series is then regressed on this design matrix using ordinary least-squares (OLS) estimation.

4.3.2 Model testing and interpretation

The significance of a particular model can be tested with an F-statistic (regression mean square/residual mean square) of the null hypothesis, H_0: all $B_{V_1,V_2,\ldots,V_n}=0$. However, since the proposed regression model has no intercept term (see Eq.(1)), the usual coefficient of determination (R^2), which measures the fit of model predictions to observed data calculated from regression sums-of-squares information, is artificially inflated (Arnold and Good, 1981; Kvalseth, 1985). An appropriate R^2 can be obtained by reapplying the same model to the data, but with an intercept term. The regression coefficients obtained from the model with an intercept are then deviations from the overall mean (rather than the means themselves in the non-intercept model), and linear combinations of them correspond to the coefficients from the non-intercept model.

An important feature of the regression model is its parsimonious treatment of interaction effects among the variables. By using categorized variables, a regression coefficient ($B_{V_1,V_2,\ldots V_n}$) is associated with each possible combination of variables similar to the ANOVA of a factorial design. A regression coefficient corresponding to the main effects in ANOVA can be obtained by collapsing over appropriate cells (i.e., adding together appropriate $B_{V_1,V_2,\ldots V_n}$). A test comparing any two regression coefficients, or any linear combination of coefficients, can be performed based on confidence intervals calculated using variance estimates from the variance/covariance matrix of the $B_{V_1,V_2,\ldots V_n}$. In this manner, the direct effects of each explanatory variable on the response variable (i.e., averaged over all variables in the model) can be calculated and compared with any combination of interaction effects. Thus, categorical regression provides a parsimonious representation of interaction effects without requiring specification of the functional forms in the model. Also, categorical regression allows investigations and comparisons of main effects and interactions via linear contrasts of the regression coefficients.

Another interpretive feature of the categorical regression time-series model is that time lags are all treated identically. In Eq.(1), there is a $B_{V_1,V_2,\ldots V_n}$ for each of the 2^n cells (columns in the design matrix). Coefficients are not specific to any particular lag, rather the model averages over time lags. Thus, each $B_{V_1,V_2,\ldots V_n}$ is interpreted as the average contribution to the present value of Y_t from the conditions associated with that cell (i.e., defined by the values of V_1, $V_2,\ldots V_n$), given the observed history of the explanatory variables. This is the reason for dividing by the number of lags (p-q+1) in Eq.(1). With coefficients estimated in this manner, the combinations of explanatory variables which lead to greater and less than average contributions to the present values of the response variable can be identified and statistically compared to the overall average contribution (i.e., average of all $B_{V_1,V_2,\ldots V_n}$) using a t-test.

Finally, in addition to the usual sources of variability observed in ecological data (e.g., limited sampling frequency, patchiness), the construction of long-term data sets usually requires synthesis from a variety of sources and can involve data obtained using different measurement methods. Use of categorized variables addresses the great uncertainty typically found in long-term ecological data. We are more apt to believe historical data characterized by categories (e.g., high and low) than by the specific values of the variables.

4.3.3 Model building

Determination of the "best" model requires a systematic method of model building, especially when numerous candidate explanatory variables are available. We recommmend that the first step in model bulding be the a priori specification of a candidate set of explanatory variabales and reasonable lags based on known or hypothesized ecological information. The approach to model building would depend on the number of candidate variables specified. If there were only a limited number of candidate variables, then some (or all) combinations of variables could be tested. If a substantial number of variables are available as candidate explanatory variables, then a variable selection procedure is needed. We have utilized a procedure (Fig. 39) similar to the forward selection method used in linear regression (Kleinbaum and Klupper, 1978). First, the model is applied to each candidate explanatory variable (i.e., for two categories, $2^1=2$ cells) and the residuals are checked for autocorrelation using a runs test (Draper and Smith, 1981). We use a runs test, rather than the commonly used Durbin-Watson statistic, because in the situation of lagged response variables appearing as explanatory variables and autocorrelated errors, the Durbin-Watson statistic is an insensitive indicator of autocorrelation (Ostrom, 1978). Based on the F-test for model significance, possible models are identified. Using the R^2 values and the results of the runs test, the "best" model is selected. Second, using the "best" model, each of the remaining candidate variables are added singly, and the model that shows a significant increase in the amount of variation explained is then designated as the "best" model. The increase in the amount of variation explained can be examined using an F-test (see Neter and Wasserman, 1974 -- general linear test) based on residual sum of squares (RSS) from the full (f) and reduced (r) models:

$$F_{[df(r)-df(f)],df(f)} = \frac{RSS(r) - RSS(f)}{df(r) - df(f)} \cdot \frac{df(f)}{RSS(f)} \qquad (2)$$

This process continues until none of the remaining candidate variables can significantly increase the amount of variation explained over the previous model. This procedure is by no means rigid, and ecological information can be used at any step to eliminate some models from consideration and/or preferentially test other models. Furthermore, criteria other than R^2 values can also be used as the basis for model building (e.g., see "optimal pruning" in Breiman et al., 1894).

An important feature of the scheme presented here is that pollution variables are tested singly against other determinants of stock size: historical stock and climatic variables affecting recruitment. Thus, the scheme results in a decision table (Fig. 40) that enables a conditional and relative determination of the importance of the pollution variate vs the climate variates. The columns in Fig. 40 indicate the statistical significance of including the tested pollution variable, given a significant model including lagged stock variables and climate variables, while the rows indicate the significance of including the climatic variables, given the lagged stock variable and pollution variable dependencies.

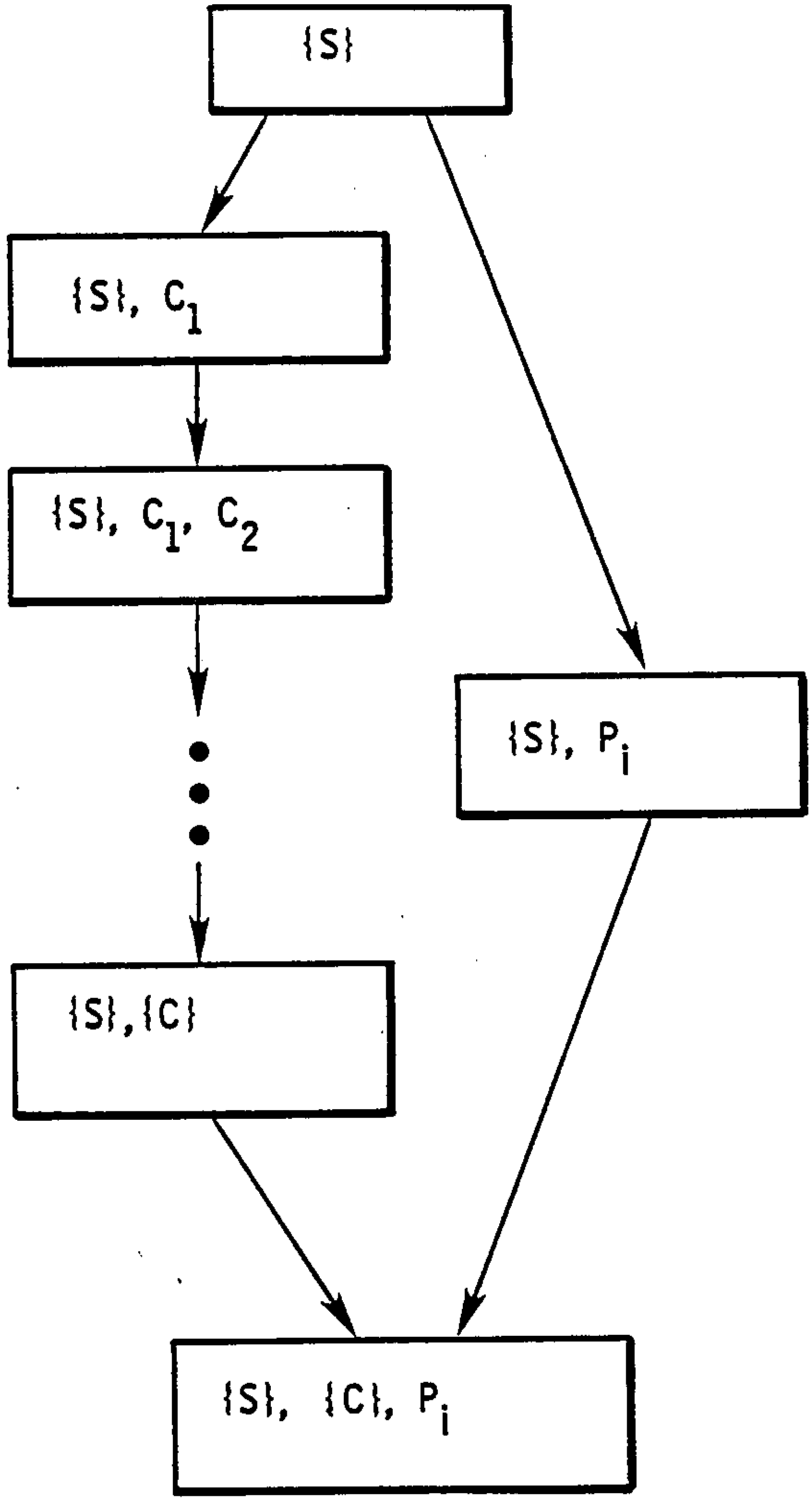

Figure 39. Model-building scheme for incorporation of climatic variables and individual pollution variables. Key: {S} = lagged stock model; {S}, C_i = lagged stock-climate models; {S},{C} = final lagged stock-climate model; {S},P_i = lagged stock-pollution models; and {S}, {C}, P_i = best lagged stock-climate-pollution model

$(\{C\} \mid \{S\}, P_i)$ \ $(P_i \mid \{S\}, \{C\})$	*	NS
*	$\{C\}$ Strong P_i Strong	$\{C\}$ Strong Relative to P_i
NS	P_i Strong Relative to $\{C\}$	Indeterminate (e.g., Collinear)

Figure 40. Decision table for classification and interpretation of model results. Key: $\{S\}$ = stock variables, $\{C\}$ = climate variables, P_i = pollution variable, * = statistically significant at $\alpha = 0.05$, and NS = not statistically significant at $\alpha = 0.05$.

The possible combinations of results obtained from following the left and right branches in Fig. 39 are as shown in Fig. 40.

- Both the climatic variable and the pollution variable are significant predictors of stock abundance
- Either the climatic variable or the pollution variable is significant
- Neither the pollution variable nor the climatic variable is significant, as a result, for example, of collinearity of the stock and extrinsic variables.

Categorical time-series regression was used throughout the project to gauge the relationships between stock, hydrographic, and anthropogenic variables and to determine the relative importance of each in contributing to variation in stock abundance of target fisheries.

5. RESULTS

The model-building scheme presented in Fig. 39 was used for all stock-estuary combinations that warranted analysis; these are listed in Table 14. Specific stock-estuary combinations were not analyzed because:

- The fish species is not found in the particular estuary (e.g., American lobster in the Potomac estuary).
- The species is found in the estuary only infrequently or in numbers too low to sustain a commercial fishery (e.g., winter flounder in the Potomac estuary).
- The species spawns, develops, and generally remains outside estuarine waters (i.e., offshore) and should not be affected by variables characterizing estuarine conditions (e.g., American pollack in Rhode Island Sound).

For analysis and interpretation, the target species can be allocated into four groups based on life history. These groups are the anadromous species, estuarine residents, ocean spawners/estuarine developers, and ocean spawners/developers (Table 15). This grouping is not simply for convenience; one of the major assumptions of the categorical time-series regression with lagged variables is that hydrographic and pollution conditions will most likely affect the early (i.e., prerecruitment) life stages of the target stocks (Polgar et al., 1985). Stocks that have similar early-life-stage characteristics and requirements can be expected to have similar responses to variations in climate or water quality.

Because so many analyses were completed for the historical fisheries/pollution program, we will primarily use tables to summarize results and will augment these tables with specific examples where warranted. The results will be described by target estuary. All discussion of the results and the hypotheses about cause-and-effect relationships will be reserved for Section 6--Discussion and Interpretation.

5.1 Potomac Estuary

Fifteen stocks were evaluated for the Potomac estuary. Table 16 lists the lagged stock and hydrographic variables used in the analyses. The hydrographic variables were chosen to represent conditions during spawning and/or developmental periods (Werme et al., 1983; DiNardo et al., 1984; Yetman et al., 1984). Cross-correlation techniques were used to identify, from the eight candidate anthropogenic (macropollution) variables, those that act similarly or consistently (Table 17), of which there were four. These were:

- A monotonic-trend variable representing human population, sewage loading, employment level, and acreage in improved farmland (the farmland trend is opposite to that of the other variables)
- Minimum 28-day average levels of dissolved oxygen during the summer at Fort Foote, MD. (near Washington, D.C.)

Table 14. Fishery and shellfishery stocks for analysis, by estuary

Fishery Stock	Estuary: Potomac	Delaware	Hudson/ Raritan	Connecticut	Narragansett
Striped bass	X	X	X		X
American shad	X	X	X	X	
Tomcod			X		
Smelt					X
Alewife	X	X	X		X
Sturgeon	X	X	X		
Butterfish	X	X	X		X
White perch	X	X	X		X
Eel	X	X	X		X
Croaker	X	X			
Spot	X	X	X		
Menhaden	X	X	X		X
Scup		X	X		X
Weakfish	X	X	X		X
Tautog			X		X
Bluefish		X	X		X
Summer flounder	X	X	X		X
Winter flounder			X		X
Oyster	X	X	X		X
Soft clam	X		X		X
Hard clam		X	X		X
Blue crab	X	X	X		
Lobster		X	X		X
Windowpane flounder					X

Table 15. Allocation of target stocks into life history groups

Anadromous Species	Estuarine Residents	Ocean Spawners/ Estuarine Developers	Ocean Spawners/ Developers
American shad	White perch	Blue crab	Scup
Striped bass	Oyster	Lobster	Tautog
Alewife	Soft clam	American Eel	
Sturgeon	Hard clam	Atlantic Croaker	
Tomcod		Spot	
Smelt		Menhaden	
		Weakfish	
		Bluefish	
		Summer flounder	
		Winter flounder	
		Windowpane flounder	
		Butterfish	

Table 16. Lagged hydrographic variables used in Potomac estuary analyses

Stock	Lag (years)	Hydrographic[a] Variables
<u>Anadromous species</u>		
Striped bass	2-6	March F,T April F,T
American shad	4-6	March F,T April F,T
Alewife	3-5	March F,T
Sturgeon[b]	7-12	
<u>Estuarine residents</u>		
White perch	5-10	March F,T April F,T
Oyster	3-6	June F,T July F,T August F,T
Soft clam	1-2	May F,T June F,T July F,T October F,T
<u>Ocean spawners/estuarine developers</u>		
Blue crab	1-2	February T March W1 April W1 May F,T June F,T
Eel	2-7	April F,T May F,T June F,T November F,T September F,T

(a) F = freshwater discharge
T = temperature
W1 = wind that creates a landward surface coastal flow
W2 = wind that creates a seaward surface coastal flow

(b) Unable to complete analyses

Table 16. (continued)

Stock	Lag (years)	Hydrographic[a] Variables
Atlantic croaker	2-7	September W2 October W2 December F,T January F,T
Spot	2-3	January W2 December W2 March F,T April F,T
Menhaden	2-3	January W1 February W1 March F,T April F,T
Weakfish	2-3	May W2 June F,T July F,T
Summer flounder	5-10	January W2 December W2 March F,T April F,T
Butterfish	2-4	July W1 August F,T,W1

Table 17. Cross-correlation of anthropogenic (macropollution) variables for the Potomac estuary[a]

	POPULATE	IMFARM	DREDGE	LODO	SIC	SEWAGE	BOD5
POPULATE	X	-0.9361	-0.2288	-0.6707	0.9868	0.9863	0.4364
IMFARM		X	0.2953	0.2557	-0.8965	-0.9388	-0.2863
DREDGE			X	-0.0031	-0.3405	-0.3012	-0.0432
LODO				X	-0.3404	-0.1596	-0.4998
SIC					X	0.9693	0.1016
SEWAGE						X	0.3425
BOD5							X

(a) POPULATE = human population.
IMFARM = acreage of improved farmland.
DREDGE = dredge volume removed between river miles 55 and 110.
LODO = minimum summertime 28-day average dissolved oxygen.
SIC = number of employees in manufacturing.
SEWAGE = sewage loading (total).
BOD5 = Five-day biochemical oxygen demand associated with sewage.

- Five-day biochemical oxygen demand (BOD) loadings from sewage discharges, a reflection of sewage treatment practices

- The volume of dredged material from the reach of the estuary that is associated with fish spawning and/or development (i.e., river miles 55-110).

These variables were used in the analyses of all Potomac stocks. For several species, time-series regressions with categorical variables yielded surprisingly good model fits to the observed data. The models accounted for at least 70% of the stock variation for 5 of the 14 Potomac stocks modeled (Table 18); these five stocks were eel (R^2 = 0.84), American shad (0.78), oyster (0.77), striped bass (0.72), and weakfish (0.70). An additional four stocks could be modeled to account for more than 55% of the stock variation.

The variables directly affecting the historical variability and the specific combination of interacting variables which significantly affect long-term variation in stock size are shown in Table 19 for stocks where 55% of their variance could be explained. An underlining of a variable showing main effects indicates a positive relationship between present stock and the lagged variable. An asterisk associated with a significant combination of lagged explanatory variables indicates that the interaction contributes to future stock levels at a rate greater than the historical average condition for the stock.

Figure 41 shows the progressive improvement in fit as model building proceeded for striped bass in the Potomac estuary. The model curve shown in Fig. 41(a) indicates a significant dependence of striped bass abundance on its historical abundance, as estimated from abundance category (high vs low) 2-6 years previously. These lagged variables were chosen on the basis of life history and exploitation pattern: striped bass are first recruited into the fishery at age 2, and make their last significant contribution to landings at age 4.

Proceeding with the model-building scheme, we added to the lagged stock values both lagged values for April river flow and lagged values for April temperature, the most complete set of independent variables. The fit of the resulting model is shown graphically in Fig. 41(b). The residuals in this model are free of significant serial correlation, as determined by a run-of-sign test (Draper and Smith, 1966). Initially, lagged December temperature was also included as an independent variable, but this turned out to be insignificant in the model.

The model curve shown in Fig. 41(c) was constructed by including a macropollution trend variable, human population, on top of the significant stock variable, but without including the climatic variables. Although this model fit is significant, the residuals are serially correlated.

The final step in building the model for Potomac River striped bass is shown in Fig. 41 (d). This model includes stock, climatic, and human population variables. Residuals are not serially correlated. The model is not significantly different, however, from that shown in Fig. 41(b).

The statistical results and model comparisons for striped bass with climatic and macropollution variables are summarized in Table 20. The R^2 values,

Table 18. Results (R^2 = values) of the Potomac estuary analyses

	Model		
Stock	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
Anadromous species			
Striped bass	0.3305	0.7173 (April T,F)	None
American shad	0.3557	0.5612 (March F)	0.7166 (LODO) 0.7754 (TREND)
Alewife	0.0422 (NS)[c,d]	0.2438 (March F)	0.4051 (TREND) 0.4626 (BOD5)
Estuarine residents			
White perch	0.3554	0.5513 (April F)	None
Oyster	0.0178 (NS)	0.5923 (August T)[e] (June T)	0.7706 (BOD5) 0.7685 (TREND) 0.7530 (LODO)
Soft clam	0.0010 (NS)	0.3862 (November T) (July T)	0.6338 (DREDGE)

(a) Significant additions to the stock model (F = river flow, T = temperature, W = wind).
(b) Significant additions to the best stock-hydrographic model. (LODO = minimum 28-day average dissolved oxygen at Fort Foote, Maryland; TREND = monotonic trend variables, see text; BOD5 = five-day biochemical oxygen demand from sewage loadings; DREDGE = volume of dredge removed.)
(c) NS = not significant at α <0.05.
(d) A significant stock model can be obtained with a lag of 2-4 years, but there is no evidence that 2-year-olds contribute to the Potomac fishery (2-year-olds generally contribute to the ocean fishery).
(e) A third hydrographic variable can be added to the oyster model: addition of June flow increases R^2 to 0.8025.

Table 18. (continued)

Stock	Model		
	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
Ocean spawners/estuarine developers			
Blue crab	0.2206	0.4258 (April)	0.6568 (TREND)
Menhaden	0.0691	0.2019 (April T)	None
Summer flounder	0.1033	None	0.2090 (TREND) 0.2411 (DREDGE) 0.3110 (BOD5) 0.2822 (LODO)
Eel	0.1725	0.5788 (May T) (June T)	0.8405 (DREDGE) 0.8179 (BOD5)
Spot	0.2219	0.2996 (December W)	None
Croaker	0.2725	0.4685 (December T)	0.6076 (POP) 0.5847 (LODO)
Weakfish	0.1631	0.2832 (July T)	0.6898 (TREND) 0.3920 (LODO) 0.5785 (BOD5)
Butterfish	-0.0171 (NS)	None	None

Table 19. Results of categorical time-series regression denoting significant stock, hydrographic, and pollution variables for models which account for greater than 55% of historical stock variation in the Potomac River

Stock	R^2	Main Effects[a]	Interactions[b,c]
Striped bass	.717	Stock	HS-HT4-HF4*
American shad	.775	Sewage	HS-LSw*
Oyster	.803	None	HS-LT8-LT6-HF6*
			LS-HT8-LT6-HF6
			HS-HT8-LT6-HF6
American eel	.841	Stock, T5, T6, Dredging	HS-LT5-LT6-LD*
Weakfish	.682	Stock, T5, Sewage	HS-HT6-LSw
Blue crab	.657	Sewage	HS-HW8-LSw*
White perch	.551	Stock, F4	HS-HF4*
Atlantic croaker	.608	None	HS-LT12-LSw*

[a] Tx, Fx, Wx = Water temperature, freshwater discharge, and wind speed and direction, respectively; x refers to specific calendar months 1 through 12 (e.g., T3 = March temperature). An underscore indicates a positive relationship between predicted stock abundance and the indicated variable(s) for direct effects; no underscore indicates a negative relationship.

[b] The naming convention for interaction terms is as follows: the first character refers to category type (H = High, L = Low); the second character refers to the variable (S = stock, T = temperature, F = flow, W = wind, Sw = sewage, DO = dissolved oxygen, D = dredging); the third chracter refers to calendar months 1 through 12 (e.g. HS-HT8-LT6-HF6 = the interaction among high stock, high August temperature, low June temperature, and high June flow conditions). If no number is included, then the conditions that existed are not month specific (e.g., LSw refers to low annual sewage loading).

[c] Indicates an interaction that produces a contribution to future stock abundance significantly greater (*), or less (no *) than the historical average contribution to stock (t-test; a = .05).

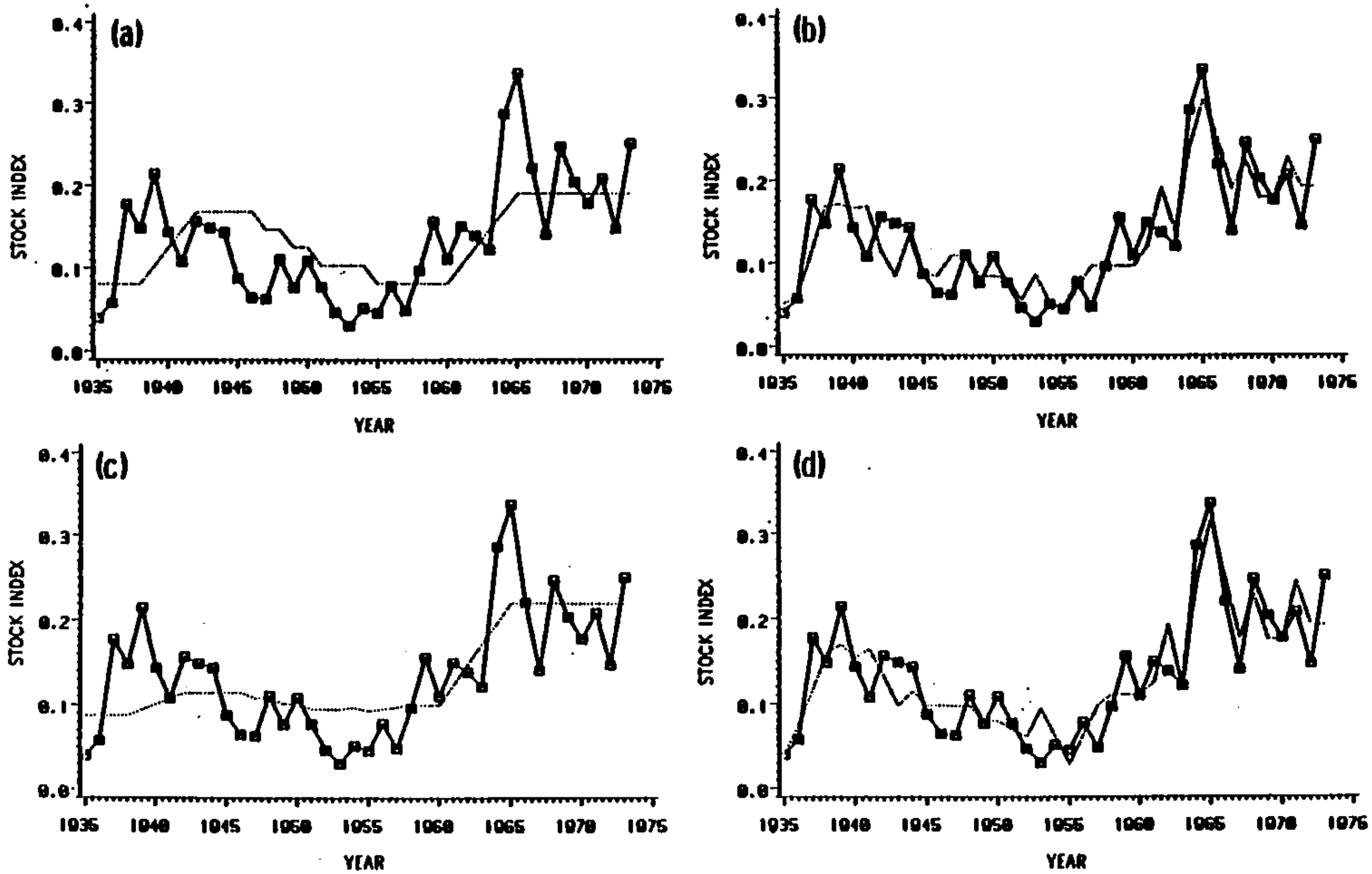

Figure 41. Models of stock variation (1935-1974) in Potomac River striped bass. Key: □□ = observed, --- = predicted. (a) Stock lagged 2-6 years; (b) stock, April river flow, and April temperature lagged 2-6 years; (c) stock and human population lagged 2-6 years; (d) stock, April river flow, April temperature, and human population lagged 2-6 years.

Table 20. Effects of climate and macropollution on abundance of striped bass in the Potomac estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.3305	---	19.76[a][b]
B. Lagged stock April temperature April flow	8	0.7173	B to A	9.46*
C. Lagged stock Sewage loadings (SEWAGE)	4	0.4783	C to A	6.24*
D. Lagged stock Dredging (TOTVOL)	4	0.3577	D to A	NS
E. Lagged stock Dissolved oxygen (LODO)	4	0.4518	E to A	5.12*
F. Lagged stock Five-day BOD (BOD5)	4	0.4165	F to A	3.75*
G. Lagged stock April temperature April flow Sewage loadings (SEWAGE)	16	0.6961	G to B	NS

[a]* = Significant at $\alpha = 0.05$.
[b]Model F-value rather than comparative F-value.

Table 20. (continued)

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
H. Lagged stock April flow April temperature Dredging (TOTVOL)	16	0.6975	H to B	NS
I. Lagged stock April temperature April flow Dissolved oxygen (LODO)	16	0.6963	I to B I to E	NS 3.80*
J. Lagged stock April temperature April flow Five-day BOD (BOD5)	16	0.7168	J to B J to F	NS 4.70*

adjusted for degrees of freedom, and their patterns among models confirm that the scheme for comparing the models is reasonable. The largest amount of variation in abundance of striped bass is explained by the model that does not include any of the macropollution variables. Striped bass stock size appears to be directly related to categorized lagged stock size 4-6 years ago (i.e., whether the parent stock was large or small). Future stock size in the Potomac River is strongly dependent upon the combination of large stock size and high river flow and temperature in April to produce good year classes for commercial recruitment (Table 19).

Figure 42 shows the progressive improvement in model fit for American shad in the Potomac estuary. The model shown in Fig. 42A indicates the dependence of shad abundance on its historical abundance (lag = 4-6 years). Shad generally first return to natal tributaries of the Potomac River at 4 years of age, and all shad have returned to spawn by age 6. We then added lagged March and April river flow and temperature; the best resulting model included March river flow only (Fig. 42B). Next, several anthropogenic variables were added to the shad models, and the macropollution trend variable (sewage loading; Fig. 42C) and the dissolved oxygen level were the strongest of those pollutant indicator variables. Sewage negatively affects stock abundance, whereas dissolved oxygen levels positively affect abundance. In fact, compared with climatic factors, macropollution trend factors are stronger determinants of shad stock variation in the Potomac River (Table 21). American shad stock size appears to be negatively related to sewage loading in the Potomac River during the spawning and developmental period, with the interaction of high stock and low sewage loading producing significantly larger than average year classes for commercial recruitment (Table 19).

Figure 43 shows the best model fit for eel stock abundance in the Potomac River (R^2 = 0.84). This model includes stock history, May and June temperatures, and dredging activity lagged 2-7 years. Eels generally establish themselves in the Potomac by age 2 and do not enter the spawning migrations to the ocean until about age 7. In this proposed model, dredging activity has a very strong negative effect on eel abundance in the Potomac River (Table 22). American eel stocks seem directly influenced by all the significant variables in the model -- stock (positive), temperatures in May and June (negative), and dredging activity (negative) -- as shown in Table 19. Higher than average future recruitment to commercial stocks (i.e., lags of 2-7 years) are shown by the combination of high stock, low May and June temperatures, and low dredging lagged appropriately (Table 19).

Figure 44 shows the best model fit for American oyster stock abundance in the Potomac River (R^2 = 0.77) incorporating a pollution variable. Lagged stock, June and August temperatures, and 5-day BOD loadings associated with sewage discharges are the variables included in this model. The BOD associated with sewage loadings is a strong positive determinant of stock abundance for oysters in the Potomac River. While climatic factors also strongly affect oyster abundance, they are not as important as sewage-related factors (Table 23) when only two hydrographic variables are used. Oyster variability can be best explained (R^2 = 0.803) when three hydrographic variables enter into the model -- June and August temperatures and June freshwater flow. None of these variables significantly affected stock size alone but the interaction of high stock, low June and August temperatures, and high June flow creates significantly larger than average future recruitment to commercial stocks (Table 19).

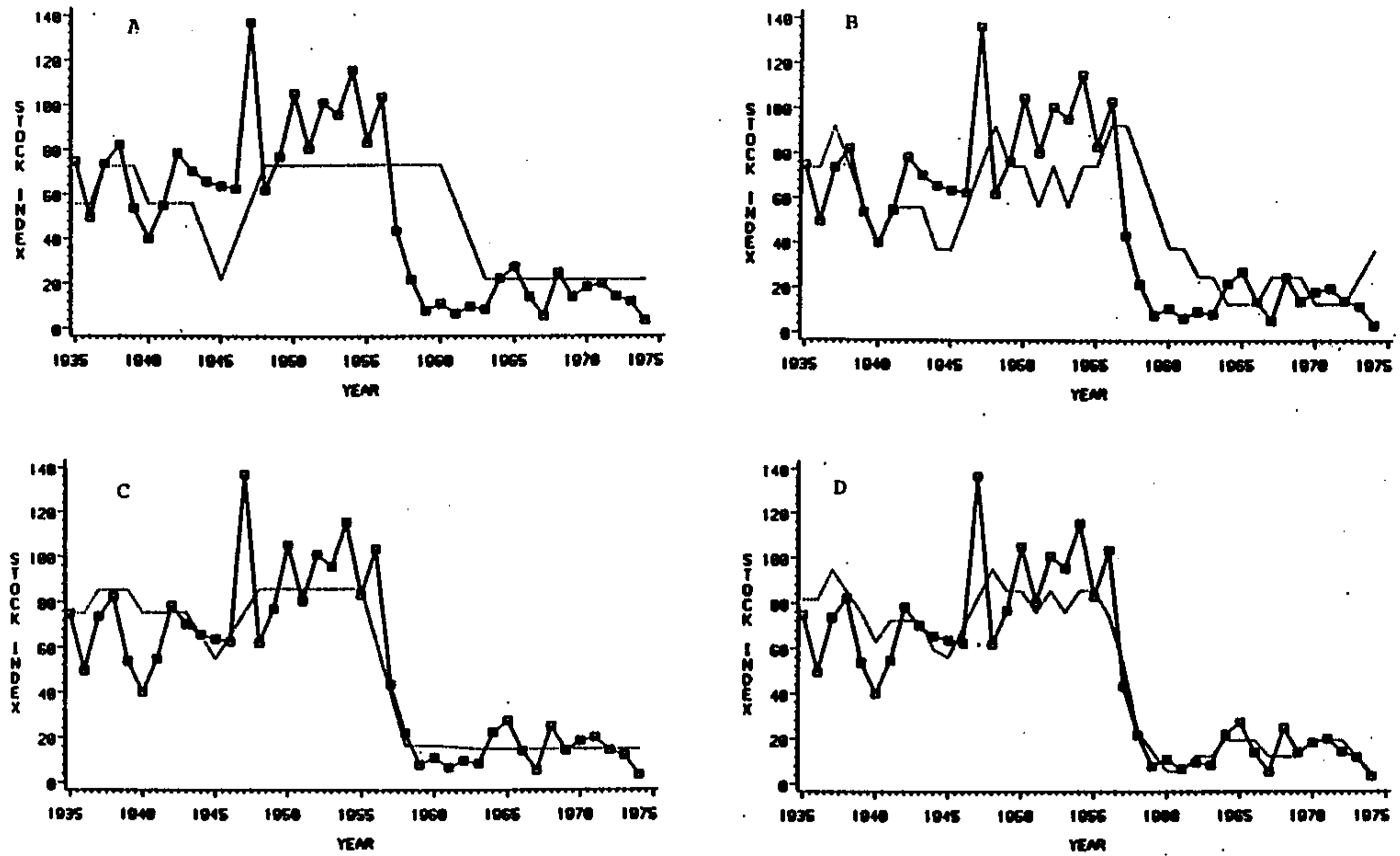

Figure 42. Models of stock variation (1935-1974) in Potomac River American shad. Key: □□ = observed, --- = predicted. (a) Stock lagged 4-6 years; (b) stock and March river flow lagged 4-6 years; (c) stock and employment levels lagged 4-6 years; (d) stock, March river flow, and employment levels lagged 4-6 years.

Table 21. Effects of climate and macropollution on abundance of American shad in the Potomac estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.3557	---	22.53*[a][b]
B. Lagged stock March flow	4	0.5612	B to A	9.90*
C. Lagged stock Sewage	4	0.7742	C to A	36.22*
D. Lagged stock Dredging (TOTVOL)	4	0.3303	D to A	NS
E. Lagged stock Dissolved oxygen (LODO)	4	0.4586	E to A	4.61*
F. Lagged stock March flow Sewage	8	0.7462	F to B F to C	12.45* NS
G. Lagged stock March flow Dredging (TOTVOL)	8	0.5339	G to B G to D	NS 4.93*
H. Lagged stock March flow Dissolved oxygen (LODO)	8	0.7166	H to B H to E	5.94* 9.19*

(a) Model F-value rather than comparative F-value.
(b) * = significant at α = 0.05.

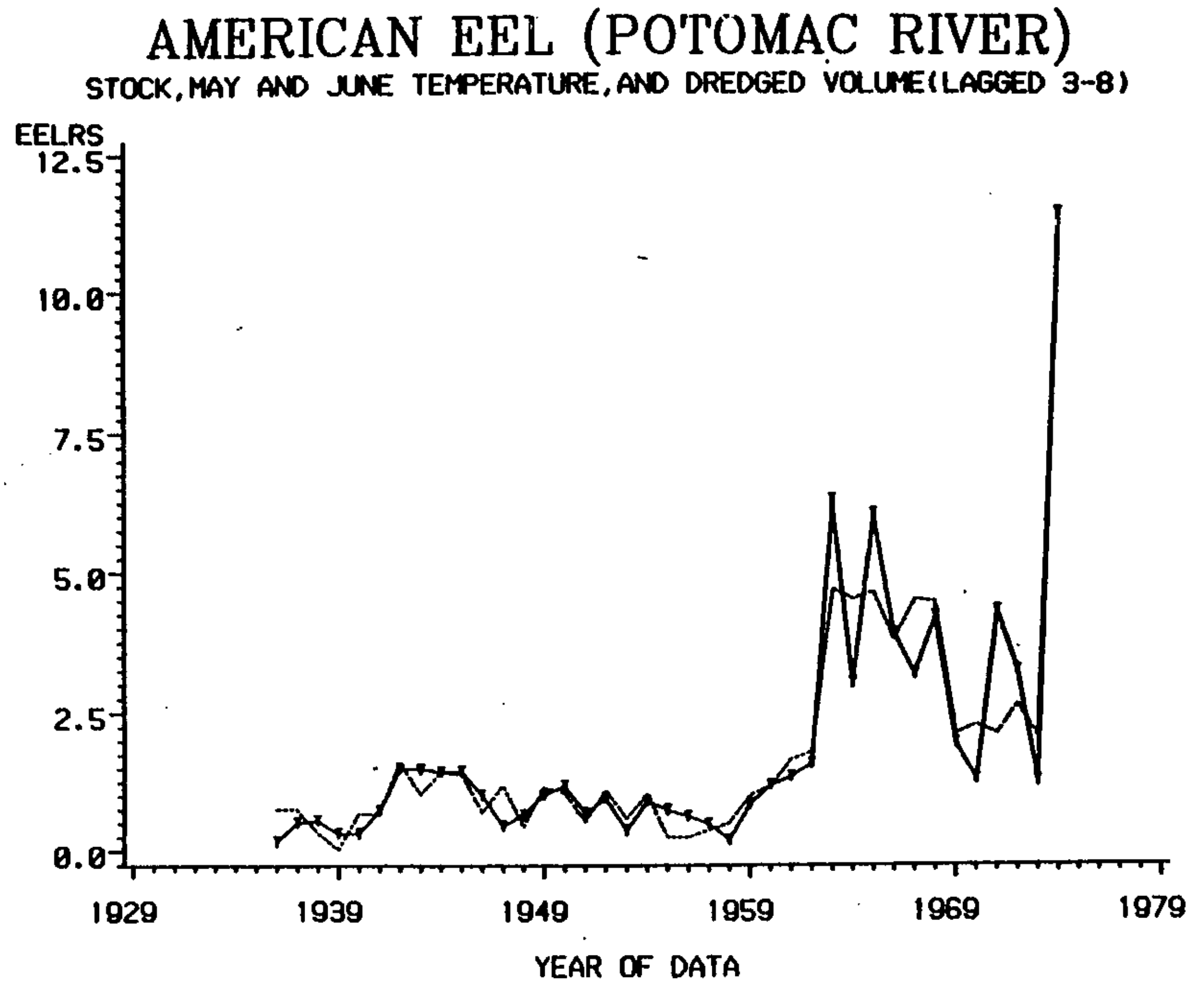

Figure 43. Model of stock variation (1936-1974) in Potomac River American eel. Key: T-T = observed, --- = predicted. Stock, May and June temperatures, and dredging activity lagged 2-7 years.

Table 22. Effects of climate and macropollution on abundance of American eel in the Potomac estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.1725	---	8.92*[a][b]
B. Lagged stock May temperature June temperature	8	0.5788	B to A	13.90*
C. Lagged stock Human population (POPULATE)	4	0.1512	C to A	NS
D. Lagged stock Dredging (TOTVOL)	4	0.2179	D to A	NS
E. Lagged stock Dissolved oxygen (LODO)	4	0.3005	E to A	4.39*
F. Lagged stock Five-day BOD (BOD5)	4	0.2668	F to A	3.38*
G. Lagged stock May temperature June temperature Human population (POPULATE)	16	0.5514	G to B G to C	NS 5.59*

(a) Model F-value rather than comparative F-value.
(b) * = significant at $\alpha = 0.05$.

Table 22. (continued)

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
H. Lagged stock May temperature June temperature Dredging (TOTVOL)	16	0.8405	H to B H to D	37.11* 31.22*
I. Lagged stock May temperature June temperature Dissolved oxygen (LODO)	16	0.6081	I to B I to E	NS 3.50*
J. Lagged stock May temperature June temperature Five-day BOD (BOD5)	16	0.8179	J to B J to F	7.79* 11.59*

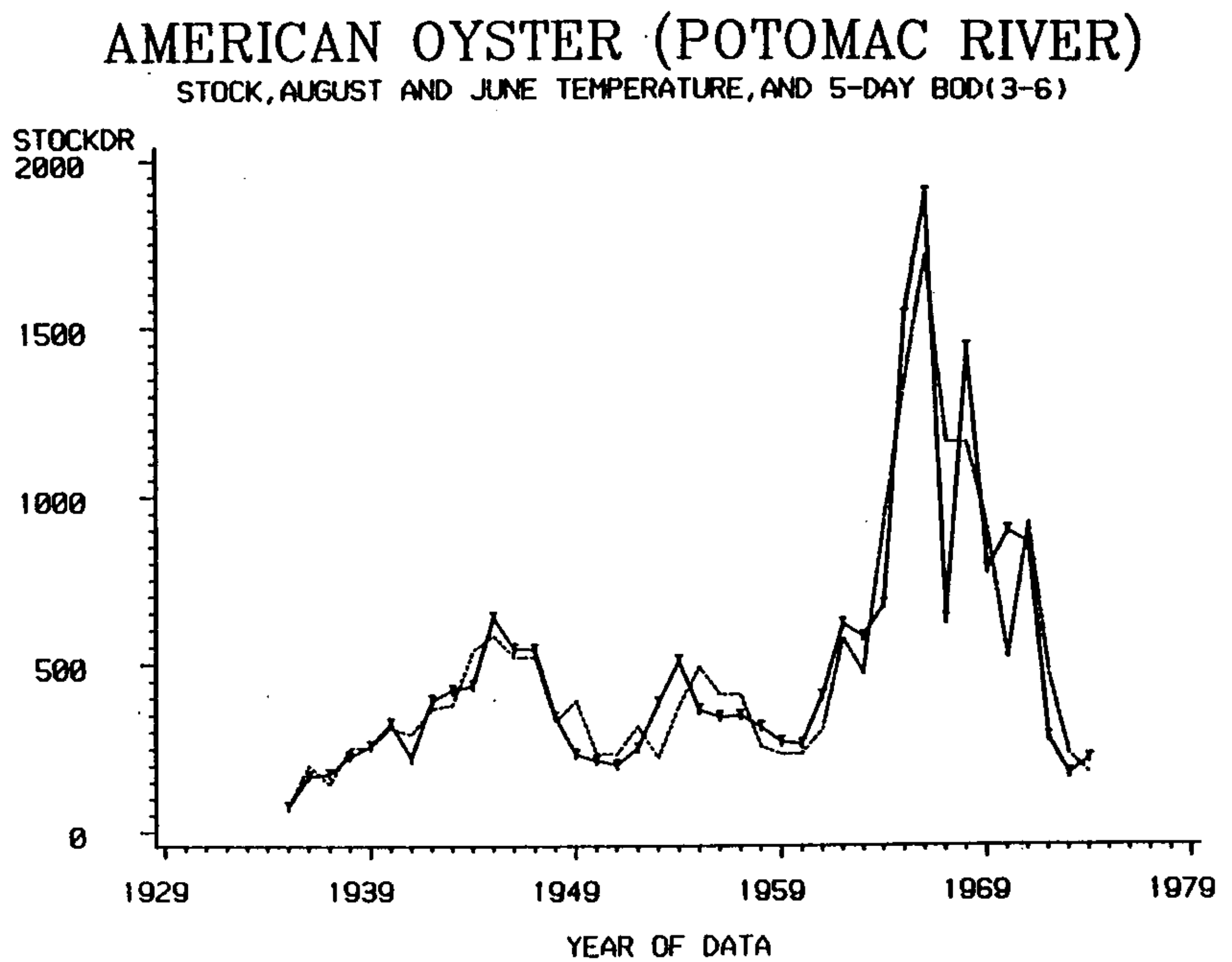

Figure 44. Model of stock variation (1935-1974) in Potomac River American oyster. Key: T-T = observed, --- = predicted. Stock, August and June temperatures, and 5-day BOD levels lagged 3-6 years.

Table 23. Effects of climate and macropollution on abundance of American oyster in the Potomac estuary

	Regressor Variables	Number of Categories	Adjusted R^2	Comparisons	
				Models	F-Value
A.	Lagged stock	2	0.0178 (NS)	---	NS[(a)]
B.	Lagged stock August temperature June temperature	8	0.5923	B to A	21.23*[(b)]
C.	Lagged stock Human population (POPULATE)	4	0.1615	C to A	4.26*
D.	Lagged stock Dredging (TOTVOL)	4	0.0834	D to A	NS
E.	Lagged stock Dissolved oxygen (LODO)	4	0.2262	E to A	6.12*
F.	Lagged stock Five-day BOD (BOD5)	4	0.5618	F to A	24.58*
G.	Lagged stock August temperature June temperature Human population (POPULATE)	16	0.7675	G to B G to C	4.44* 9.53*

[(a)] Model F-value rather than comparative F-value.
[(b)] * = significant $\alpha = 0.05$.

Table 23. (continued)

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
H. Lagged stock August temperature June temperature Dredging (TOTVOL)	16	0.6703	H to B H to D	NS 6.83*
I. Lagged stock August temperature June temperature Dissolved oxygen (LODO)	16	0.7530	I to B I to E	3.60* 7.40*
J. Lagged stock August temperature June temperature Five-day BOD (BOD5)	16	0.7706	J to B J to F	4.55* 3.98*
K. Lagged stock August temperature June temperature June flow	16	0.8025	K to B	5.86*

Figure 45 shows the best model fit for weakfish stock abundance in the Potomac River. Lagged stock, July temperature, and sewage loading are the variables composing this model. The negative effect of sewage loading on stock abundance is stronger than the effect of July temperature on stock abundance (Table 24). Interactions of these variables appear to play a minor role in the variability of weakfish stock size (Table 19).

For 8 of the 12 stocks on which the relative effects of anthropogenic and hydrographic factors could be compared, the association of anthropogenic factors with stock abundance was as least as strong as that of hydrographic factors (Table 25). In only one (striped bass) of the five well-modeled stocks ($R^2 > 0.70$) were anthropogenic factors not a major source of stock variation. The majority of the associations between stock abundance and anthropogenic factors in the Potomac system were related to sewage and BOD loadings.

5.2 Delaware Estuary

Eighteen stocks were evaluated for the Delaware River estuary. Table 26 lists the lagged stock, hydrographic, and anthropogenic variables used in the analyses. Obviously, the same climate-month combinations found to be important in the Potomac system may or may not be important to Delaware stocks. Thus, the hydrographic variables for the Delaware analyses were specifically chosen to represent conditions during the spawning and/or developmental periods of Delaware stocks (Werme et al., 1983; DiNardo et al., 1984; Yetman et al., 1984).

Anthropogenic variables were cross-correlated to reveal potential collinearities (Table 27). This procedure reduced the number of candidate macropollution variables from eight to four, namely:

- A monotonic-trend variable representing human population, acreage of improved farmland, sewage loadings, and BOD loadings associated with sewage discharges

- Volume dredged between miles 90 and 135 of the Delaware River

- Volume dredged between the mouth of Delaware Bay and river mile 90, and total volume dredged between the mouth of the bay and river mile 135

- Minimum summer concentrations of dissolved oxygen observed between river miles 48 and 134.

In the Delaware estuary, unlike the Potomac estuary, sewage and sewage-associated BOD loadings were strongly correlated ($R^2 = 0.959$). This finding suggests that most sewage discharged into the Delaware River near Philadelphia and Camden has received a relatively constant level of treatment throughout the period of historical study.

By use of categorical time-series regressions, models accounting for at least 65% of stock variation could be constructed for 6 of the 18 stocks studied (Table 28); these six stocks were scup ($R^2 = 0.82$), white perch (0.82), summer flounder (0.75), croaker (0.67), bluefish (0.67), and oyster (0.65).

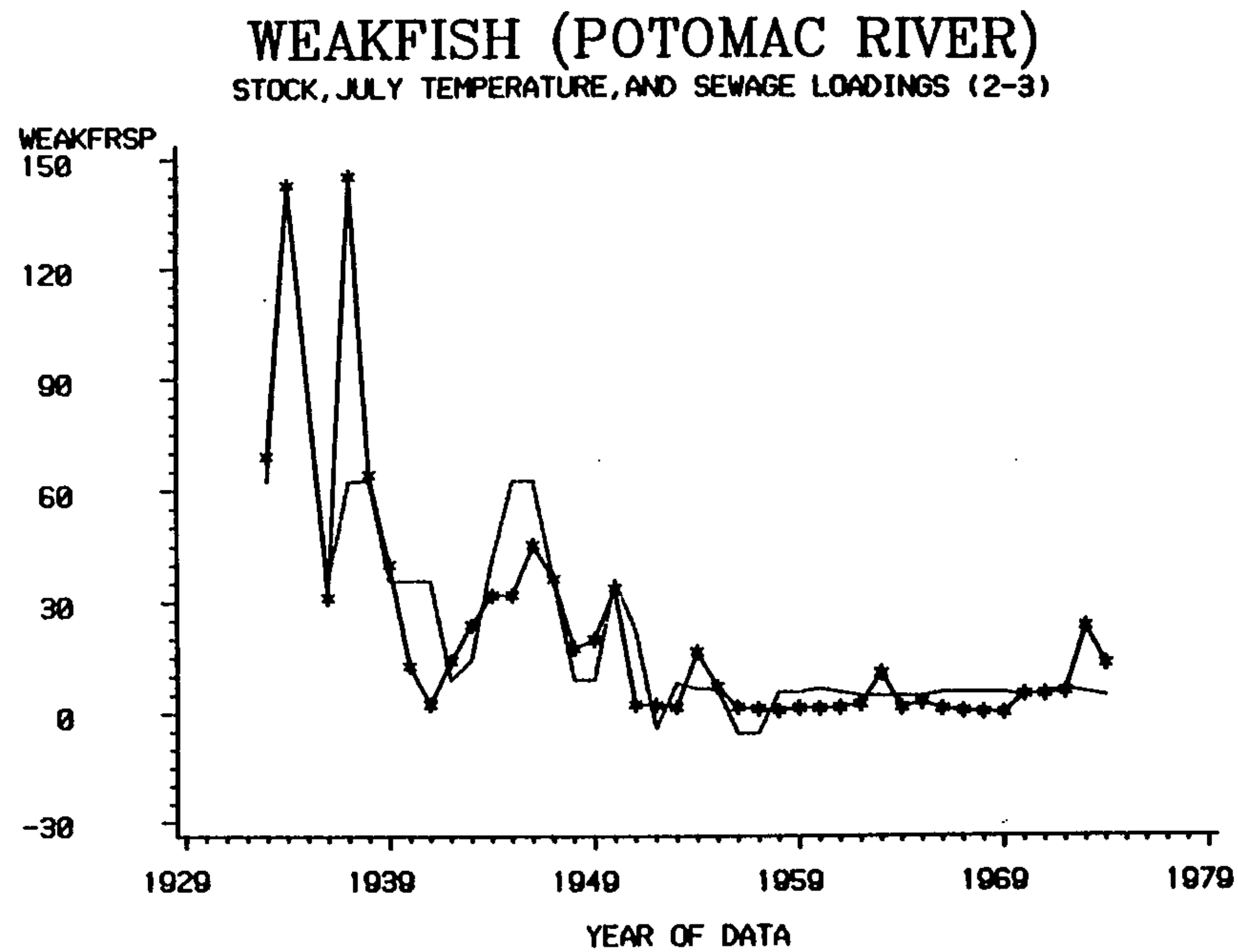

Figure 45. Model of stock variation (1934-1974) in Potomac River weakfish. Key: *—* = observed, --- = predicted. Stock, July temperature, and sewage loadings lagged 2-3 years.

Table 24. Effects of climate and macropollution on abundance of weakfish in the Potomac estuary

	Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A.	Lagged stock	2	0.1631	---	8.79*[a][b]
B.	Lagged stock July temperature	4	0.2832	B to A	4.27*
C.	Lagged stock Sewage loadings (SEWAGE)	4	0.3508	C to A	6.64*
D.	Lagged stock Dredging (TOTVOL)	4	0.2023	D to A	NS
E.	Lagged stock Five-day BOD (BOD5)	4	0.4313	E to A	10.20*
F.	Lagged stock July temperature Sewage loadings (SEWAGE)	8	0.6821	F to B F to C	12.61* 10.64*
G.	Lagged stock July temperature Dredging (TOTVOL)	8	0.3383	G to B G to D	NS 2.90*
H.	Lagged stock July temperature Five-day BOD (BOD5)	8	0.5785	H to B H to E	9.64* 5.31*

(a) Model F-value rather than comparative F-value.
(b) * = Significant at $\alpha = 0.05$.

Table 25. Relative strengths of associations between stock abundance, climate, and macropollution variables for the Potomac estuary[a]

Stock	Macropollution Variables						
	Human Population (POPULATE)	Dredging (DREDGE)	Improved Farmland (IMFARM)	Dissolved Oxygen (LODO)	No. of Employees (SIC)	Five-day BOD (BOD5)	Sewage Loadings (SEWAGE)
Striped bass	2	2	2	2	2	2	2
American shad	3	2	3	1	3	1	3
Alewife	3	2	1	2	1	1	1
White perch	2	4	2	2	2	2	2
Oyster	1	2	1	1	1	1	1
Soft clam	2	1	2	2	2	4	2
Blue crab	1	2	1	2	1	2	1
Menhaden	2	4	2	2	2	2	2

[a]Key:

1 = both climate and pollution are important.
2 = climate is more important than pollution.
3 = pollution is more important than climate.
4 = second variable is nonsignificant when first variable is significant (potential collinearity of climate and pollution).

Table 25. (continued)

Stock	Macropollution Variables						
	Human Population (POPULATE)	Dredging (DREDGE)	Improved Farmland (IMFARM)	Dissolved Oxygen (LODO)	No. of Employees (SIC)	Five-day BOD (BOD5)	Sewage Loadings (SEWAGE)
Eel	2	1	2	2	2	1	2
Spot	4	4	4	4	4	4	4
Atlantic croaker	1	2	2	1	2	2	2
Weakfish	1	2	1	1	1	1	1

Table 26. Lagged variables used in Delaware estuary analyses

Stock	Lag (years)	Variables: Hydrographic[a]	Variables: Anthropogenic[b]
Anadromous species			
American shad	4-6	March F,T April F,T	T, VOL135, MINDO
Striped bass	2-6	April F,T May F,T	T, VOL135, MINDO
Sturgeon	7-12	March F,T April F,T May F,T	T, VOL135, MINDO
Alewife	4-5	March F,T April F,T May F,T	T, VOL135, MINDO

(a) F = river flow.
T = temperature.
W1 = wind from S to E.
W2 = wind from N to W.

(b) T = macropollution trend variables.
VOL90 = total volume dredged from river miles 0-90.
VOL135 = total volume dredged from river miles 90-135.
MINDO = minimum concentration of dissolved oxygen.

Table 26. (continued)

Stock	Lag (years)	Variables: Hydrographic[a]	Variables: Anthropogenic[b]
Estuarine residents			
Oyster	3-7	June F,T July F,T August F,T	T, VOL90, MINDO
Hard clam	2-7	May F,T June F,T July F,T	T, VOL90, MINDO
White perch	3-8	April F,T May F,T	T, VOL135, MINDO
Ocean spawners/estuarine developers			
Blue crab	1-2	April W1 May W1 June F,T,W1 July F,T,W1 August F,T,W1	T, VOL90, MINDO
Menhaden	2-3	March W1 May F,T June F,T October W1	T, VOL90, MINDO

Table 26. (continued)

Stock	Lag (years)	Variables	
		Hydrographic[a]	Anthropogenic[b]
Weakfish	3-4	June F,T July F,T August F,T	T, VOL90, MINDO
Bluefish	2-7	June F,T July F,T	T, VOL90, MINDO
Lobster	6-10	April F,T May F,T	T, VOL90, MINDO
Eel	2-7	June F,T July F,T August F,T	T, DREDGE, VOL135, MINDO
Summer flounder	5-10	May F,T June F,T July F,T	T, VOL90, MINDO
Spot	2-3	December W2 January W2 May F,T June F,T	T, VOL90, MINDO
Croaker	2-4	October W2 November W2,F,T December F,T	T, VOL90, MINDO
Butterfish	2-4	June F,T July F,T August F,T	T, VOL90, MINDO

Table 26. (continued)

Stock	Lag (years)	Variables: Hydrographic[a]	Anthropogenic[b]
<u>Ocean</u>			
Scup	3-6	June W1 July W1,F,T August F,T	T, VOL90, MINDO

Table 27. Cross-correlation of anthropogenic (macropollution) variables for the Delaware estuary

	POPULATE	DREDGE	VOL90	VOL135	MINDO	IMFARM	SEWAGE	BOD
POPULATE[a]	1.00000	0.39152	0.36057	0.19824	0.73301	-0.94620	0.96648	0.92857
DREDGE	0.39152	1.00000	0.97534	0.26895	-0.35142	-0.45228	-0.47619	-0.45901
VOL90	0.36057	0.97534	1.00000	0.04973	-0.42114	-0.40745	-0.50267	-0.48061
VOL135	0.19824	0.26895	0.04973	1.00000	0.28008	-0.26698	0.07799	0.05977
MINDO	0.73301	-0.35142	-0.42114	0.28008	1.00000	-0.83804	0.68533	0.62952
IMFARM	-0.94620	-0.45228	-0.40745	-0.26698	-0.83804	1.00000	-0.89283	-0.82960
SEWAGE	0.96648	-0.47619	-0.50267	0.07799	0.68533	-0.89283	1.00000	0.95875
BOD	0.92857	-0.45901	-0.48061	0.05977	0.62952	-0.82960	0.95875	1.00000

[a] POPULATE = human population.
DREDGE = total volume dredged between river miles 0 and 135.
VOL90 = total volume dredged between river miles 0 and 90.
VOL135 = total volume dredged between river miles 90 and 135.
MINDO = Minimum summertime concentration of dissolved oxygen between river miles 48 and 134.
IMFARM = acreage of improved farmland.
SEWAGE = sewage loadings from Philadelphia and Camden.
BOD = biochemical oxygen demand loadings from sewage discharges.

Table 28. Results (R^2 values) of the Delaware estuary analyses

	Model		
Stock	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
Anadromous species			
Striped bass	-0.0080 (NS)	0.2631 (April F) (May F)	0.3569 (MINDO)
Shad	0.0300 (NS)	0.1886 (April F)	0.5333 (TREND) 0.4547 (MINDO)
Alewife	0.1175	0.2074 (March T)	None
Sturgeon	-0.0051 (NS)	0.0797 (May T)	0.1201 (TREND) 0.1410 (MINDO)

[a] Significant additions to the stock model:
F = river flow.
T = temperature.
W1 = wind that creates a landward surface coastal flow.
W2 = wind that creates a seaward surface coastal flow.

[b] Significant additions to the best stock-hydrographic model:
TREND = monotonic trend variables (see text).
MINDO = minimum concentration of dissolved oxygen.
VOL90 = dredging activity between river miles 0 and 90.
VOL135 = dredging activity between river miles 90 and 135.

Table 28. (continued)

Stock	Model		
	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
Estuarine residents			
Oyster	0.1005	0.4700 (July F) (June T)	0.6491 (MINDO) 0.6041 (VOL90)
Hard clam	-0.0237 (NS)	0.4988 (June F) (June T)	None
White perch	0.3038	0.8209 (April T) (May F)	None
Ocean spawners/estuarine developers			
Blue crab	0.1662	0.2499 (August W1)	0.3618 (TREND) 0.3966 (MINDO)
Menhaden	0.1707	0.3785 (October W1)	None
Lobster	0.2925	0.5827 (April T)	None
Summer flounder	0.3142	0.6812 (May F)	0.7459 (VOL90) 0.7375 (MINDO)
Weakfish	0.5617	0.5898 (April F)	None
Bluefish	0.3245	0.6731 (June T)	None
Eel	-0.0166 (NS)	0.1027 (July F)	0.2666 (VOL135) 0.2443 (MINDO)

Table 28. (continued)

Stock	Model: Stock Alone	Model: Hydrographic Variables[a]	Model: Anthropogenic Variables[b]
Spot	0.2125	0.3345 (December W2)	None
Croaker	0.3560	0.6689 (October W2) (November F)	None
Butterfish	0.2979	0.3840 (June F)	0.5127 (MINDO) 0.5068 (TREND)
<u>Ocean spawners/developers</u>			
Scup	0.3810	0.5143 (August T)	0.8162 (TREND) 0.7871 (MINDO)

The variables directly affecting historical stock variability as well as the specific combinations of variables which are significant are shown in Table 29.

Figure 46 shows the best model fit for white perch stock abundance in the Delaware River estuary. This model includes stock history, April temperature, and May river flow lagged 3-8 years. White perch are resident stocks and generally enter the fyke net and pond net fisheries at age 3, while larger perch enter the gill net fisheries targeted for other species (e.g., shad) much later (age 6+). Hydrographic variables can explain 82% of the white perch stock variation, and no anthropogenic variable tested significantly improves the model fit (Table 30). White perch stock size in the Delaware Bay appears to be strongly related to variability in May freshwater flow (negative) and April temperature (positive). The interaction of high stock levels, low May flow, and high April temperature creates significantly greater than average future recruitment to commercial stocks (Table 29).

Oyster stock abundance could best be modeled from stock history, July river flow, June temperature, and dredging activity lagged 3-7 years (Fig. 47). Oyster stock abundance seems to have decreased by a factor of 5-10 from the mid-1940's to 1960, and then steadily increased from 1960 to the mid-1970's, reaching its pre-World War II levels. The combination stock-climate-macropollution model clearly follows this pattern. While minimum summertime concentration of dissolved oxygen is clearly the strongest single factor affecting oyster stock abundance in the Delaware estuary, the interaction of dredging activity with the hydrographic variabiles is stronger than the combination of dissolved oxygen levels with hydrography (Table 31). The positive relationship to water quality can account for about 56% of stock variation, without including any hydrographic variables (Table 31). Oyster stock size seems largely affected by direct relationships rather than interactions (Table 30). Strong negative relationships between stock size and dredging activity and June flow and a positive relationship to June temperature appear to control long-term variability.

The time series for several of the Delaware stocks that were well modeled (i.e., scup, summer flounder, croaker; $R^2 \geq 0.67$) may be misleading (Figs. 48 to 50). The relative stock abundance measures for these fisheries dropped to zero around 1950 and remained there through 1975, essentially as a result of no reported catch in the Delaware Bay proper after 1950. This zero catch may be real, resulting from legislative restrictions on particular types of gear, or the reduction may be artificial: the catch sizes for years before 1946 were calculated from county catches. Thus, the pre-1946 catches may be ocean rather than estuarine harvests. Regardless, the stock levels of any fishery would be unlikely to decline to zero and remain there while fisheries in neighboring regions (e.g., Hudson River, Chesapeake Bay, New Jersey coast) remain productive for the same fish species.

A number of Delaware stocks appear to be modeled acceptably even though the R^2 values associated with the model fit are low (< 0.50). In essence, the time patterns (i.e., trends) of relative stock abundance are well represented by the models for striped bass, American shad, and eel, but the modeled values do not always precisely correspond to the observed values (Figs. 51 to 53). Striped bass and American shad stock abundances (Figs. 51 and 52) are positively associated with minimum concentrations of dissolved oxygen in the Delaware River. Both hydrographic variables and dissolved oxygen appear to be important factors in stock abundance for these fisheries (Tables 32 and 33).

Table 29. Results of categorical time-series regression denoting significant stock, hydrographic, and pollution variables for models which account for greater than 55% of historical stock variation in the Delware Bay

Stock	R^2	Main Effects[a]	Interactions[b,c]
White perch	.821	F5, T4	HS-LF5-HT4*
Oyster	.649	F6, T6, Dredging	None
Lobster	.583	T4	HS-LT4*
Weakfish	.590	Stock	HS-LF4*
Bluefish	.673	Stock, T6	HS-LT6*,LS-LT6
Hard clam	.563	F6	HS-LF6-HT6-LSw*

(a) Tx, Fx, Wx = Water temperature, freshwater discharge, and wind speed and direction, respectively; x refers to specific calendar months 1 through 12 (e.g., T3 = March temperature). An underscore indicates a positive relationship between predicted stock abundance and the indicated variable(s) for direct effects; no underscore indicates a negative relationship.

(b) The naming convention for interaction terms is as follows: the first character refers to category type (H = High, L = Low); the second character refers to the variable (S = stock, T = temperature, F = flow, W = wind, Sw = sewage, DO = dissolved oxygen, D = dredging); the third chracter refers to calendar months 1 through 12 (e.g. HS-HT8-LT6-HF6 = the interaction among high stock, high August temperature, low June temperature, and high June flow conditions). If no number is included, then the conditions that existed are not month specific (e.g., LSw refers to low annual sewage loading).

(c) Indicates an interaction that produces a contribution to future stock abundance significantly greater (*), or less (no *) than the historical average contribution to stock (t-test; a = .05).

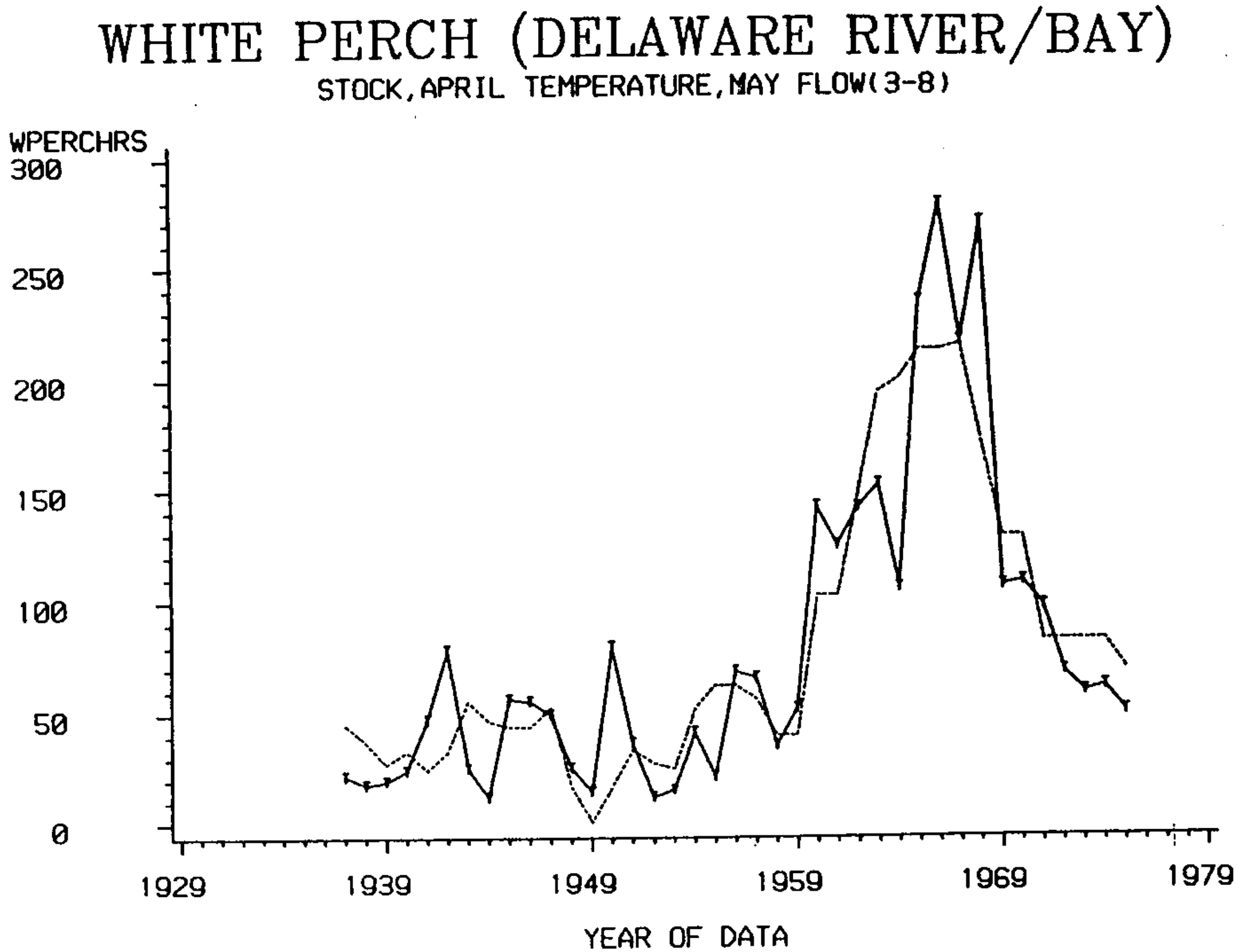

Figure 46. Model of stock variation (1937-1975) in Delaware estuary white perch. Key: T-T = observed, --- = predicted. Stock, May river flow, and April temperature lagged 3-8 years.

Table 30. Effects of climate and macropollution on abundance of white perch in the Delaware estuary.

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons Models	Comparisons F-Value
A. Lagged stock	2	0.3038	---	17.58*[a][b]
B. Lagged stock April temperature May flow	8	0.8209	B to A	27.49*
C. Lagged stock Sewage loading (SEWAGE)	4	0.4829	C to A	7.41*
D. Lagged stock Dredging (VOL135)	4	0.6677	D to A	21.26*
E. Lagged stock Dissolved oxygen (MINDO)	4	0.5059	E to A	8.57*
F. Lagged stock April temperature Sewage loading (SEWAGE)	16	0.8050	F to B G to D	NS 7.42*
G. Lagged stock May flow May temperature Dredging (VOL135)	16	0.7985	G to B G to D	NS 3.27*
H. Lagged stock April temperature May flow Dissolved oxygen (MINDO)	16	0.8403	H to B H to E	NS 9.14*

[a] Model F-value rather than comparative F-value.
[b] * = significant at $\alpha = 0.05$.

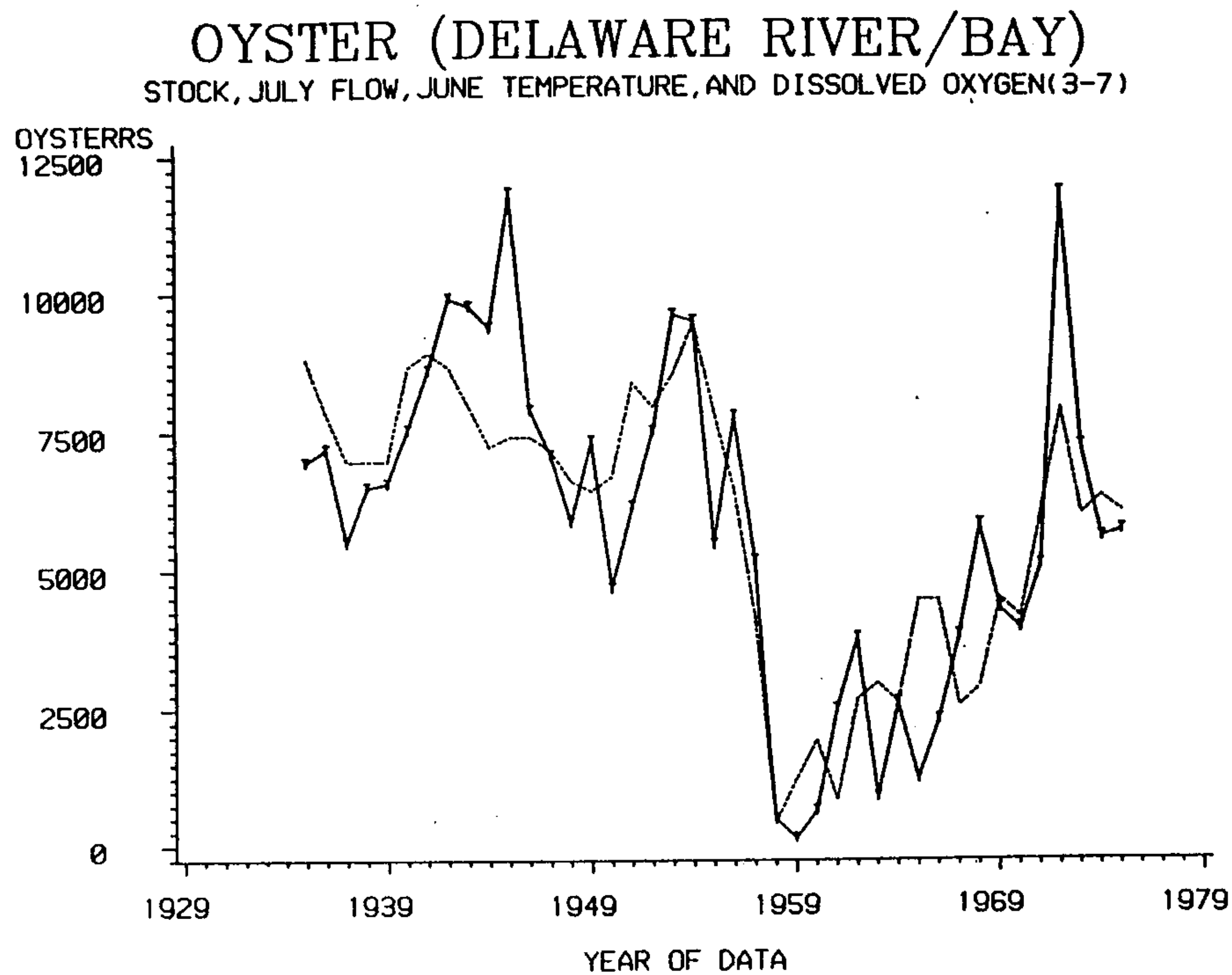

Figure 47. Model of stock variation (1935-1975) in Delaware estuary oyster. Key: T-T = observed, --- = predicted. Stock, July river flow, June temperature, and dissolved oxygen lagged 3-7 years.

Table 31. Effects of climate and macropollution on abundance of oysters in the Delaware estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons	
			Models	F-Value
A. Lagged stock	2	0.1005	---	5.36*[a][b]
B. Lagged stock June temperature July flow	8	0.4770	B to A	10.07*
C. Lagged stock Human population (POPULATE)	4	0.3084	C to A	6.70*
D. Lagged stock Dredging (VOL90)	4	0.0829	D to A	NS
E. Lagged stock Dissolved oxygen (MINDO)	4	0.5627	E to A	21.08*
F. Lagged stock June temperature July flow Human population (POPULATE)	16	0.5614	F to B F to C	NS 3.60*
G. Lagged stock July flow June temperature Dredging (VOL90)	16	0.6491	G to B G to D	3.24* 6.28*
H. Lagged stock July flow June temperature Dissolved oxygen (MINDO)	16	0.6041	H to B H to E	2.71* NS

[a]Model F-value rather than comparative F-value.
[b]* = significant at $\alpha = 0.05$.

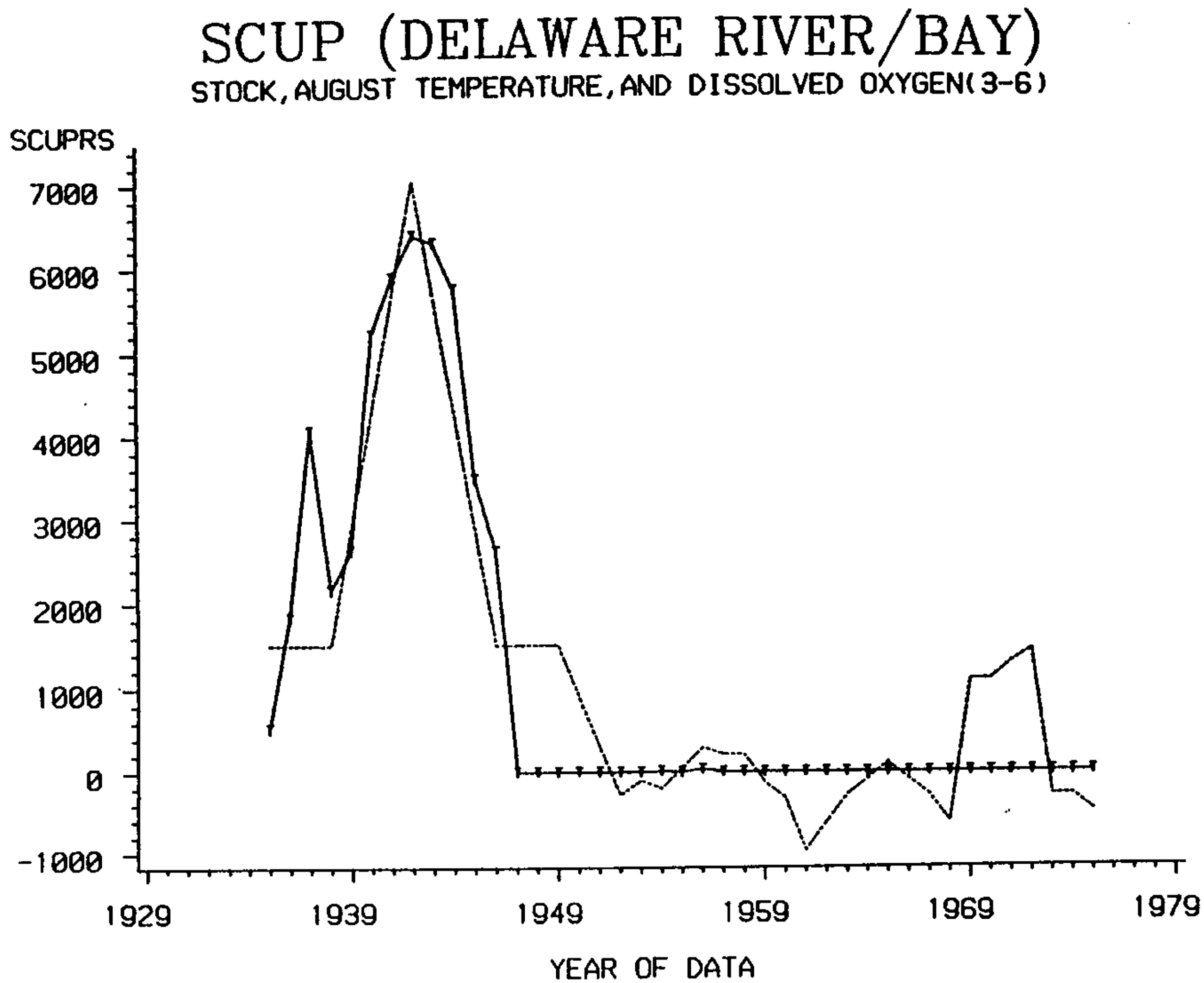

Figure 48. Model of stock variation (1935-1975) in Delaware estuary scup. Key: T-T = observed, --- = predicted. Stock, August temperature, and dissolved oxygen lagged 3-6 years.

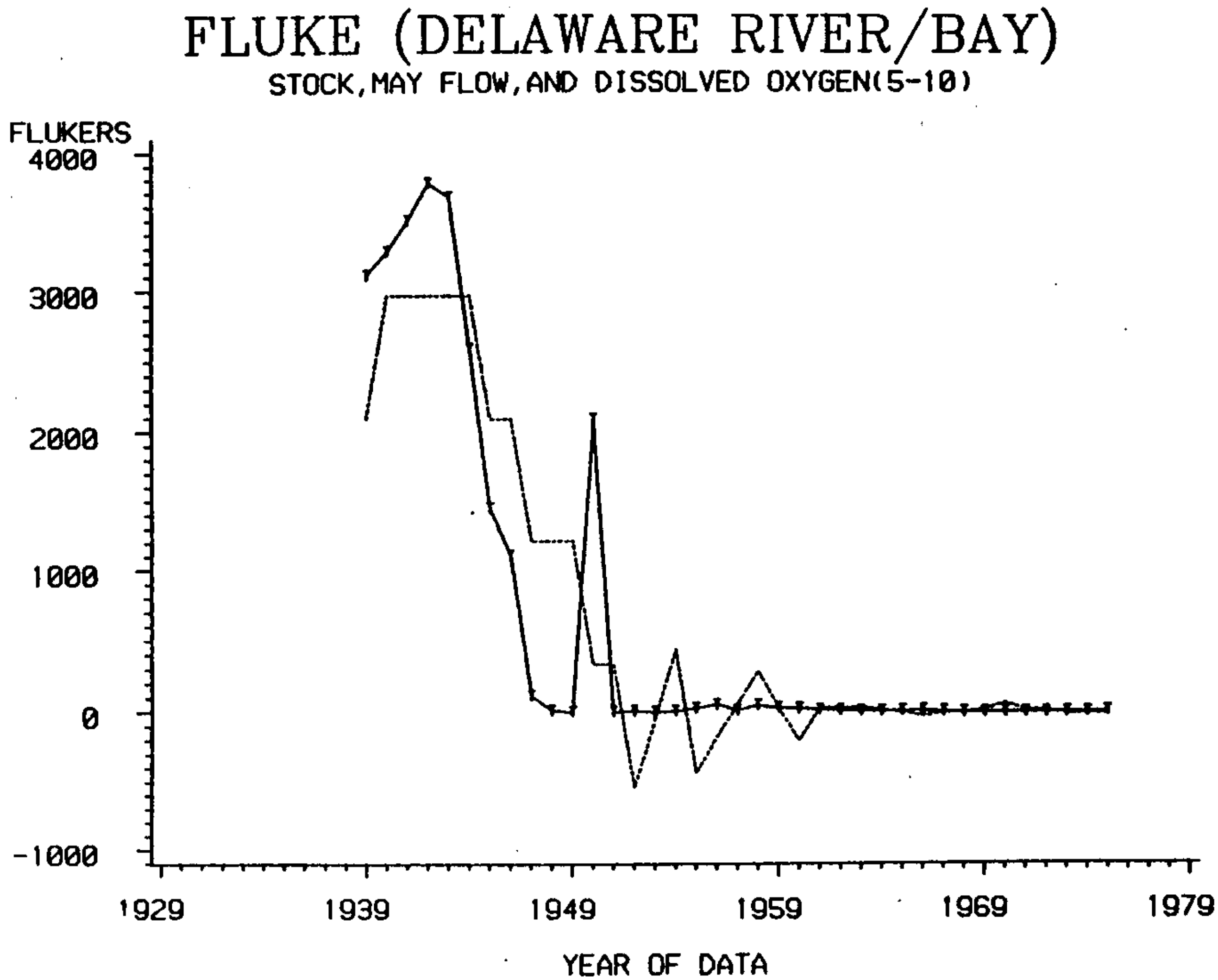

Figure 49. Model of stock variation (1939-1975) in Delaware estuary summer flounder. Key: T-T = observed, --- = predicted. Stock, May river flow, and dissolved oxygen lagged 5-10 years.

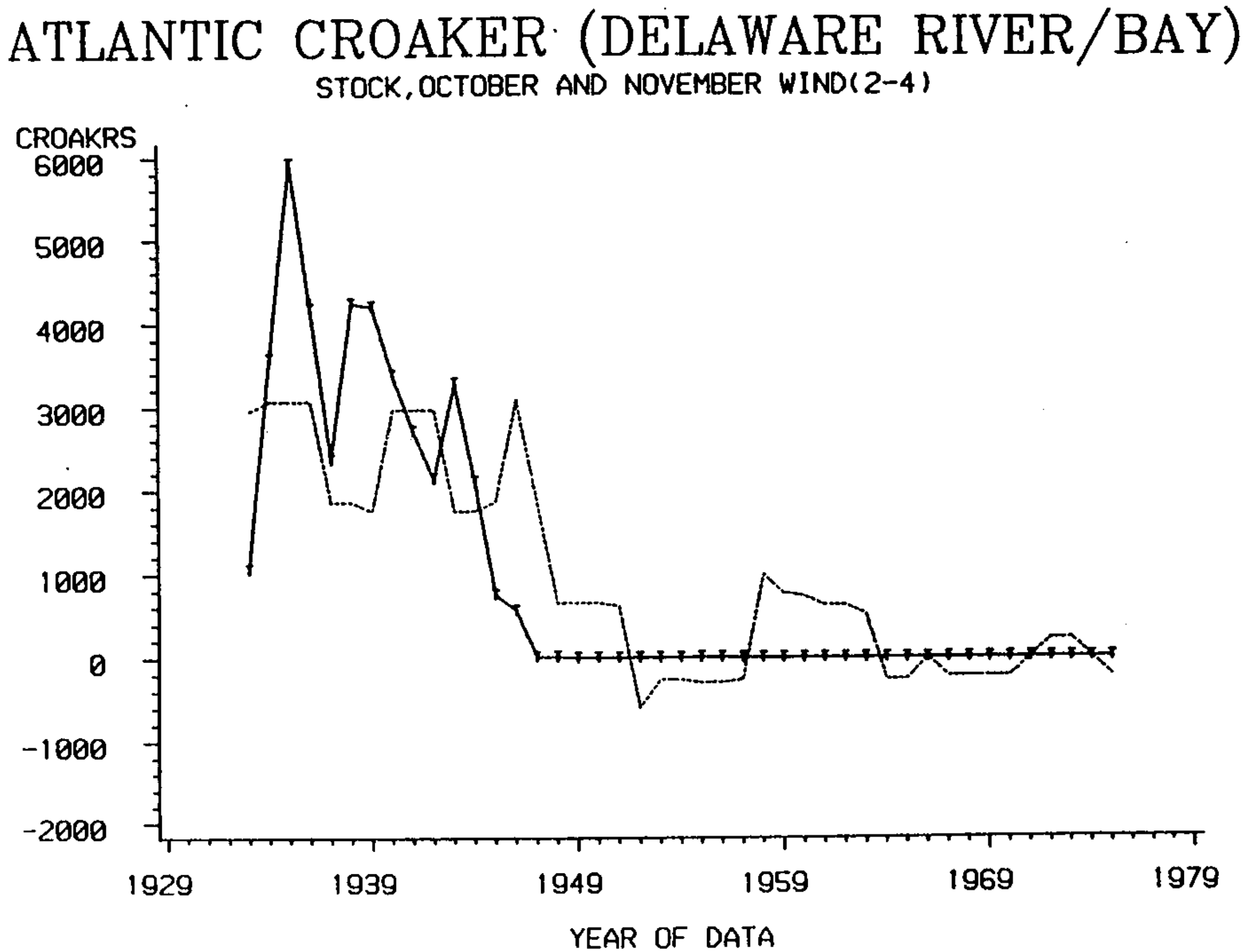

Figure 50. Model of stock variation (1932-1975) in Delaware estuary croaker. Key: T-T = observed, --- = predicted. Stock, and October and November wind (previous year), lagged 2-4 years.

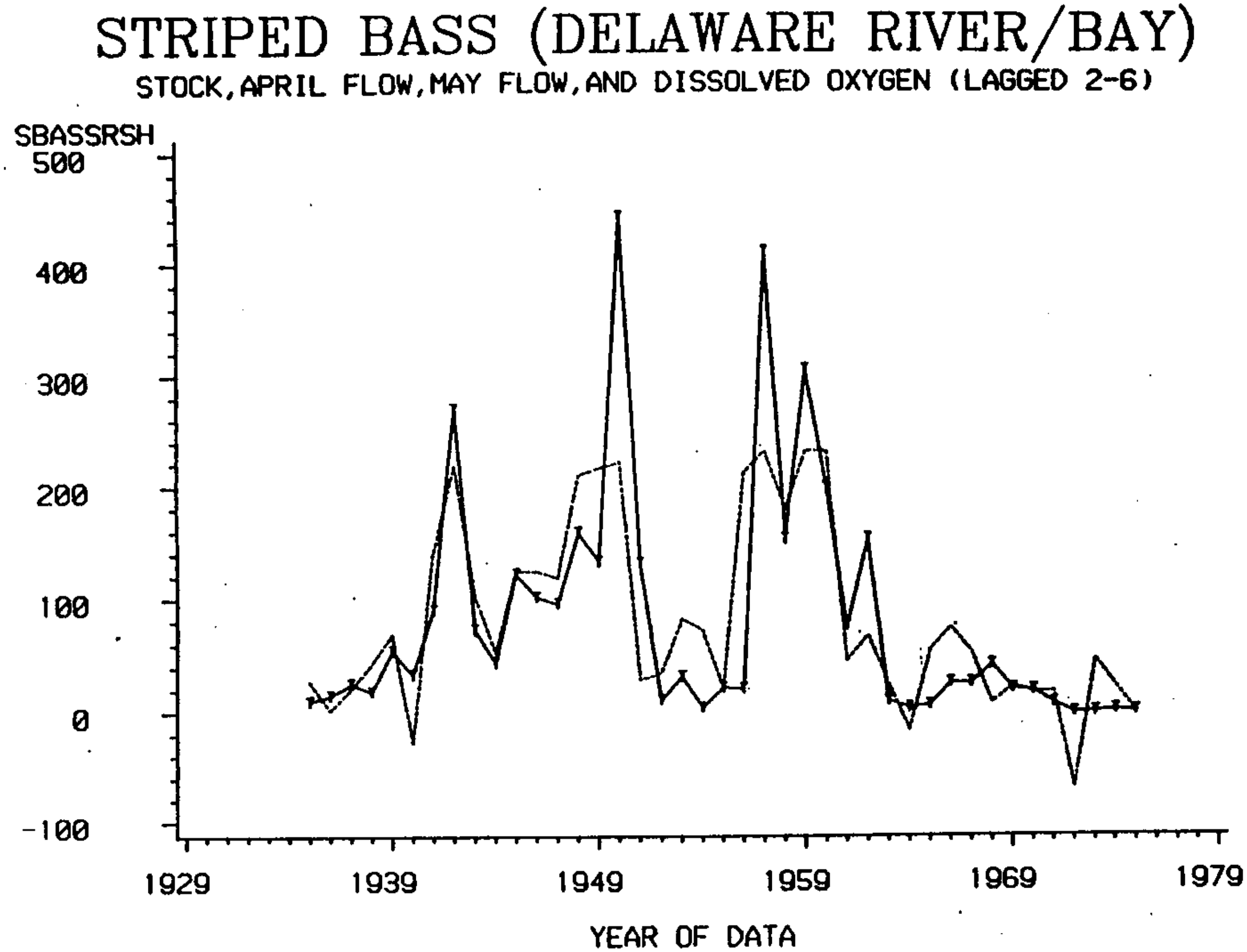

Figure 51. Model of stock variation (1935-1975) in Delaware estuary striped bass. Key: T-T = observed, --- = predicted. Stock, April river flow, May river flow, and dissolved oxygen lagged 2-6 years.

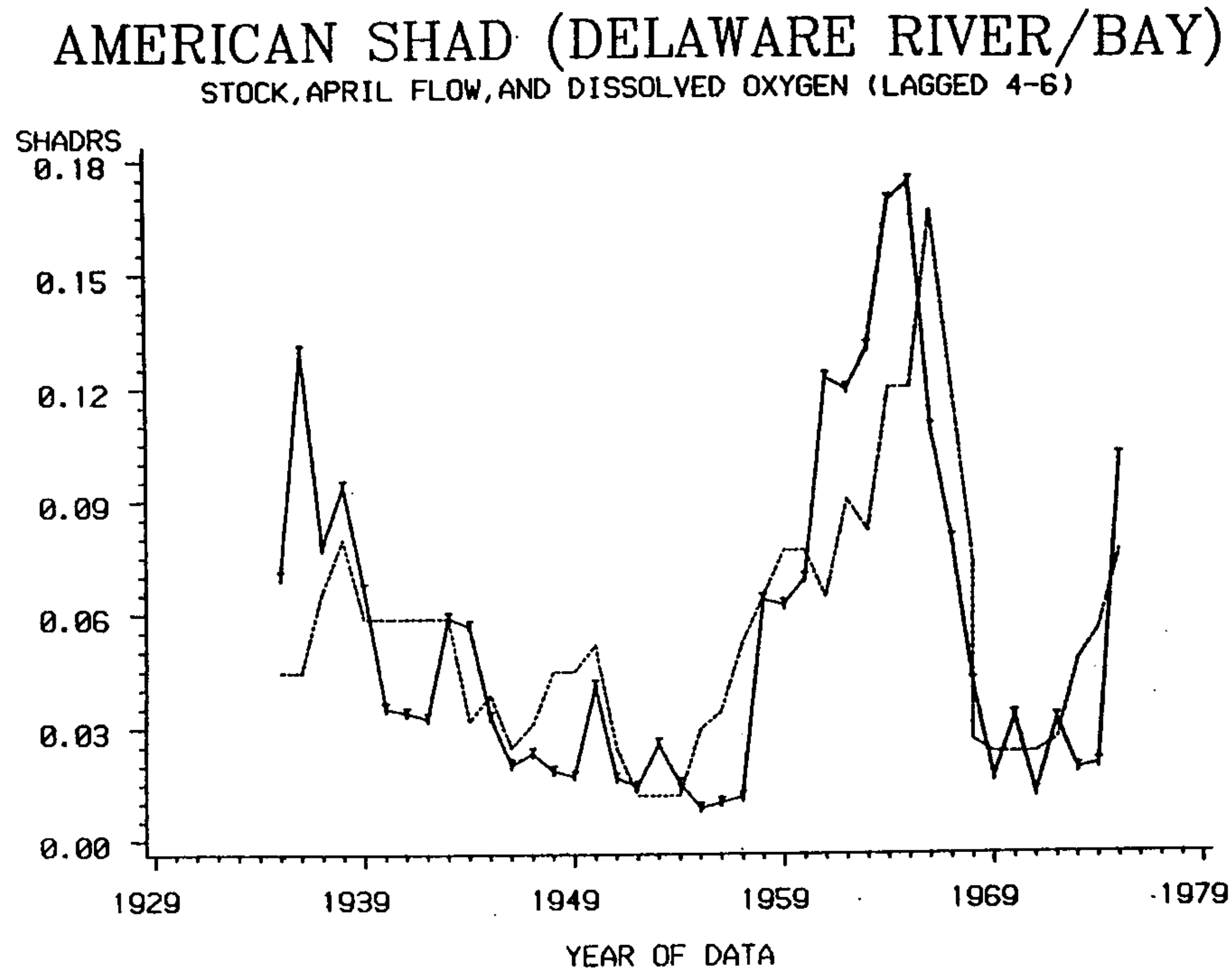

Figure 52. Model of stock variation (1935-1975) in Delaware estuary American shad. Key: T-T = observed, --- = predicted. Stock, April river flow, and dissolved oxygen lagged 4-6 years.

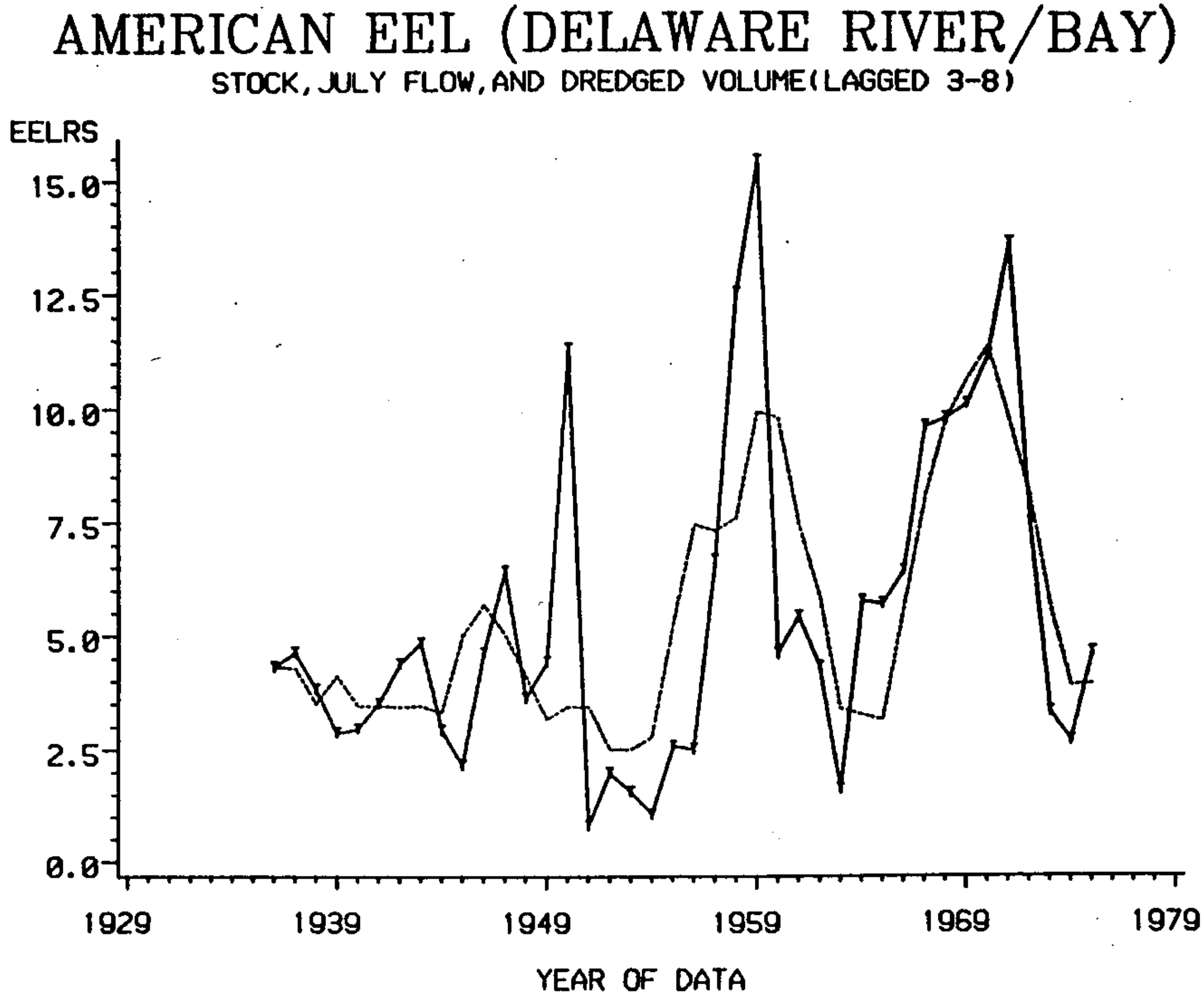

Figure 53. Model of stock variation (1935-1975) in Delaware estuary eel. Key: T-T = observed, --- = predicted. Stock, July river flow, and dredged volume lagged 3-8 years.

Table 32. Effects of climate and macropollution on abundance of striped bass in the Delaware estuary

	Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A.	Lagged stock	2	-0.0077 (NS)	---	NS[(a)]
B.	Lagged stock April temperature May flow	8	0.2631	B to A	6.62*[(b)]
C.	Lagged stock Sewage loading (SEWAGE)	4	0.0254	C to A	NS
D.	Lagged stock Dredging (VOL135)	4	-0.0321	D to A	NS
E.	Lagged stock Dissolved oxygen (MINDO)	4	-0.0124	E to A	NS
F.	Lagged stock May flow April flow Sewage loading (SEWAGE)	16	0.1747	F to B F to C	NS NS
G.	Lagged stock April flow May flow Dredging (VOL135)	16	0.2262	G to B G to D	NS 2.12*
H.	Lagged stock April flow May flow Dissolved oxygen (MINDO)	16	0.3569	H to B H to E	2.60* 3.77*

(a)Model F-value rather than comparative F-value.
(b)* = significant at $\alpha = 0.05$.

Table 33. Effects of climate and macropollution on abundance of American shad in the Delaware estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.0300	---	NS [a]
B. Lagged stock April flow	4	0.1886	B to A	4.91* [b]
C. Lagged stock Sewage loading (SEWAGE)	4	0.1874	C to A	4.87*
D. Lagged stock Dredging (VOL135)	4	0.3430	D to A	0.53*
E. Lagged stock Dissolved oxygen (MINDO)	4	0.1265	E to A	3.21*
F. Lagged stock April flow Sewage loading (SEWAGE)	8	0.5333	F to B F to C	8.02* 8.04*
G. Lagged stock April flow Dredging (VOL135)	8	0.3619	G to B G to D	3.58* NS
H. Lagged stock April flow Dissolved oxygen (MINDO)	8	0.4547	H to B H to E	5.64* 6.72*

[a] Model F value rather than comparative F value.
[b] * = significant at $\alpha = 0.05$.

Eel stock abundances (Table 34) are positively associated with hydrographic variables and dredging activity between river miles 90 and 135.

For 9 of the 18 stocks on which the relative effects of anthropogenic and hydrographic factors could be compared, the association of anthropogenic factors with stock abundance was as least as strong as that of hydrographic factors (Table 35). Of the nine stocks, most were positively associated with concentrations of dissolved oxygen in the estuary.

5.3 Hudson-Raritan Estuary

Twenty-one stocks were evaluated for the Hudson-Raritan estuary. Table 36 lists the lagged stock, hydrographic, and anthropogenic variables used in the analyses. The hydrographic variables were chosen to represent conditions prevalent during spawning and/or developmental periods for the target stocks (Werme et al., 1983; DiNardo et al., 1984; Yetman et al., 1984). All candidate macropollution variables were cross-correlated (Table 37), a procedure that left eight variables for analysis. These are:

- A monotonic-trend variable representing the increase in human population and decrease in improved farmland in the basin, as well as increases in total sewage and BOD loadings to the Hudson River and Newark Bay
- Total sewage and BOD loadings to Raritan Bay
- Dredged volume in the Hudson-Raritan system (i.e., removed from river miles 0-165 of the Hudson River and parts of the Raritan and Harlem Rivers and Arthur Kill)
- Total dredged volume in the Hudson River between river miles 40 and 165
- Four dissolved-oxygen variables separated by region (Hudson River, Upper New York Bay, Kill Van Kill, and Arthur Kill).

Categorical regressions for the Hudson/Raritan estuary resulted in good model fits ($R^2 > 0.70$) for eight stocks (Table 38); these stocks were striped bass ($R^2 = 0.86$), tomcod (0.84), weakfish (0.81), lobster (0.77), American shad (0.76), scup (0.73), hard clam (0.72), and soft clam (0.72). An additional six stocks were modeled with R^2 values between 0.45 and 0.70. The direct effects of modeled variables and the interaction of these variables, which produces significantly greater than average recruitement to commercial stocks in the Hudson/Raritan Estuary, are shown in Table 39.

Figure 54 shows the best model for relative abundance of Hudson/Raritan striped bass. The model includes the dependence of stock abundance on previous stock levels, April river flow, May temperature, and volume of dredge material removed from the spawning grounds. Hydrographic factors are very strongly associated with the year-class success of this stock. The strong stock relationship (Table 40) may reflect a strong association between future fishery success and fishing mortality. Dredging affects stock abundance positively, but is a relatively minor contributor to the overall model (Table 40). Striped bass stock variability can also be explained by three hydrographic variables.

Table 34. Effects of climate and macropollution on abundance of eel in the Delaware estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	-0.0166	---	NS[a]
B. Lagged stock July flow	4	0.1027	B to A	3.53*[b]
C. Lagged stock Human population (POPULATE)	4	0.2165	C to A	6.65*
D. Lagged stock Dredging (VOL135)	4	0.0391	D to A	NS
E. Lagged stock Dissolved oxygen (MINDO)	4	0.1425	E to A	4.52*
F. Lagged stock July flow Human population (POPULATE)	8	0.2184	F to B F to C	NS NS
G. Lagged stock July flow Dredging (VOL135)	8	0.2666	G to B G to D	3.01* 3.79*
H. Lagged stock July flow Dissolved oxygen (MINDO)	8	0.2443	H to B H to E	2.69* NS

[a] Model F value rather than comparative F value.
[b] * = significant at $\alpha = 0.05$.

Table 35. Relative strengths of associations between the stock abundance, climate, and macropollution variables for the Delaware estuary[a]

Stock	Macropollution Variables		
	TREND	DREDGING	MINDO
Striped bass	4	2	2
American shad	1	3	1
Alewife	4	4	4
Sturgeon	3	4	3
White perch	2	2	2
Oyster	2	1	3
Hard clam	2	2	2
Blue crab	3	2	3
Lobster	2	2	2
Menhaden	2	2	2
Weakfish	4	2	4
Bluefish	2	2	2
Eel	4	1	3
Summer flounder	2	1	1
Spot	4	1	2
Croaker	2	2	2
Butterfish	1	4	1
Scup	1	4	1

[a] Key:
1 = both climate and pollution are important.
2 = climate is more important than pollution.
3 = pollution is more important than climate.
4 = second variable is nonsignificant when first variable is significant (potential collinearity of climate and pollution).

Table 36. Lagged variables used in Hudson/Raritan estuary analyses.

Stock	Lag (years)	Variables: Hydrographic[a]	Variables: Anthropogenic[b]
Anadromous species			
Striped bass	2-6	April F,T May F,T	T, TOTVOL, VOL40, DOH
American shad	4-8	March F,T April F,T May F,T	T, TOTVOL, VOL40, DOH
Alewife	4-5	March F,T April F,T May F,T	T, TOTVOL, VOL40, DOH
Sturgeon	7-12	April F,T May F,T	T, TOTVOL, VOL40, DOH
Tomcod	1-3	January F,T February F,T March F,T April F,T	T, TOTVOL, VOL40, DOH
Estuarine residents			
White perch	3-8	April F,T May F,T	T, TOTVOL, VOL40, DOH
Hard clam	2-7	June F,T July F,T August F,T	T, TOTVOL, DOK, DOA SEWRAR

[a] F = river flow.
T = temperature.
W = wind.

[b] T = macropollution trend variables.
TOTVOL = dredging activity between river miles 0 and 165 of the Hudson River and portions of the Raritan-Harlem Rivers and Arthur Kill.
VOL40 = dredging activity in the Hudson River between river miles 40 and 165.
DOH = dissolved oxygen (Hudson River).
DOU = dissolved oxygen (Upper Bay).
DOA = dissolved oxygen (Arthur Kill).
DOK = dissolved oxygen (Kill Van Kull).
SEWRAR = sewage (Raritan Bay).

Table 36. (continued)

Stock	Lag (years)	Variables: Hydrographic[a]	Variables: Anthropogenic[b]
Soft clam	2-4	May F,T June F,T July F,T	T, TOTVOL, DOK, DOA, SEWRAR
Oyster	3-7	June F,T July F,T August F,T	T, TOTVOL, DOK, DOA, DOU, SEWRAR
<u>Ocean spawners/estuarine developers</u>			
Blue crab	1-2	April W May W June F,T July F,T	T, TOTVOL, DOU
Menhaden	2-3	March W April W May F,T June F,T July F,T	T, TOTVOL, DOU
Lobster	6-10	April W,F,T May W,F,T	T, TOTVOL, DOU
Summer flounde	5-10	January W February W April F,T May F,T	T, TOTVOL, DOU
Weakfish	2-3	May W June W,F,T July F,T	T, TOTVOL, DOU
Bluefish	2-7	June F,T July F,T	T, TOTVOL, DOU
Butterfish	2-4	May W June F,T July F,T	T, TOTVOL, DOU
Eel	2-7	May F,T June F,T	T, TOTVOL, DOU
Striped bass	2-6	April F,T May F,T	T, TOTVOL, VOL40, DOH

Table 36. (continued)

Stock	Lag (years)	Variables: Hydrographic[a]	Variables: Anthropogenic[b]
Spot	1-3	December W January W March F,T April F,T	T, TOTVOL, DOU
Winter flounder	2-3	February F,T March F,T April F,T	T, TOTVOL, DOU
<u>Ocean spawners/developers</u>			
Scup	3-6	June W July W,F,T August F,T September F,T	T, TOTVOL, DOU
Tautog	2-5	April W May W June F,T	T, TOTVOL, DOU

Table 37. Cross-correlations of anthropogenic (macropollution) variables for the Hudson/Raritan estuary

	POPULATE	DREDGE	DOH	DOU	DOK	DOA	IMFARM	SEWHUD	BODHUD	SEWNEW	BODNEW	SEWRAR	BODRAR	VOL40
POPULATE	1.00000	0.57963	0.01151	-0.44761	-0.49277	-0.62509	-0.98136	0.92404	0.94119	0.92449	0.95714	0.79425	0.77356	0.16676
DREDGE	0.57963	1.00000	-0.02512	-0.13943	-0.14714	-0.00386	-0.56981	-0.21607	-0.18929	-0.17121	-0.14923	-0.11570	-0.01121	0.42299
DOH	0.01151	-0.02512	1.00000	0.66751	0.64514	-0.00388	-0.02633	0.43014	0.41891	0.42045	0.43396	0.40653	0.40782	-0.28114
DOU	-0.44761	-0.13943	0.66751	1.00000	0.77003	0.05547	0.41224	0.51581	0.50689	0.53573	0.55343	0.54571	0.54146	-0.11974
DOK	-0.49277	-0.14714	0.64514	0.77003	1.00000	0.38388	0.46464	0.12731	0.11894	0.13694	0.15288	0.23156	0.22822	-0.14377
DOA	-0.62509	-0.00386	-0.00388	0.05547	0.38388	1.00000	0.58701	-0.60083	-0.59910	-0.56040	-0.57178	-0.36753	-0.36595	0.18472
IMFARM	-0.98136	-0.56981	-0.02633	0.41224	0.46464	0.58701	1.00000	-0.97203	-0.96783	-0.98596	-0.98935	-0.89804	-0.87526	-0.15523
SEWHUD	0.92404	-0.21607	0.43014	0.51581	0.12731	-0.60083	-0.97203	1.00000	0.98361	0.97522	0.81150	0.91432	0.73318	-0.28580
BODHUD	0.94119	-0.18929	0.41891	0.50689	0.11894	-0.59910	-0.96783	0.98361	1.00000	0.97559	0.88007	0.90471	0.79898	-0.28142
SEWNEW	0.92449	-0.17121	0.42045	0.53573	0.13694	-0.56040	-0.98596	0.97522	0.97559	1.00000	0.87529	0.94674	0.81101	-0.23491
BODNEW	0.95714	-0.14923	0.43396	0.55343	0.15288	-0.57178	-0.98935	0.81150	0.88007	0.87529	1.00000	0.78046	0.87448	-0.22343
SEWRAR	0.79425	-0.11570	0.40653	0.54571	0.23156	-0.36753	-0.89804	0.91432	0.90471	0.94674	0.78046	1.00000	0.84546	-0.14626
BODRAR	0.77356	-0.01121	0.40782	0.54146	0.22822	-0.36595	-0.87526	0.73318	0.79898	0.81101	0.87448	0.84546	1.00000	-0.11263
VOL40	0.16676	0.42299	-0.28114	-0.11974	-0.14377	0.18472	-0.15523	-0.28580	-0.28142	-0.23491	-0.22343	-0.14626	-0.11263	1.00000

Table 38. Results (R^2 values) of the Hudson/Raritan estuary analyses

Stock	Model: Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
Anadromous species			
Striped bass	0.4360	0.7880 (April F)[c] (May T)	0.8573 (VOL40)
American shad	0.0087	0.4691 (April F,T)	0.7581 (TOTVOL) 0.7050 (DOH) 0.6887 (VOL40)
Alewife	0.0080 (NS)[d]	0.2930 (March T,F)	0.4740 (TOTVOL) 0.3660 (VOL40)
Sturgeon	0.0760	0.4060 (April T)	None
Tomcod	0.2386	0.6894 (January T) (April F)	0.8441 (VOL40) 0.8320 (TOTVOL)

(a) Significant additions to the stock model. Key: F = river flow, T = temperature, W = wind.

(b) Significant additions to the best stock-hydrographic model. Key: VOL40 = dredging activity in the Hudson River between river miles 40 and 165, TOTVOL = dredging activity between river miles 0 and 165 of the Hudson River and parts of the Raritan-Harlem Rivers and Arthur Kill, DOH = dissolved oxygen (Hudson River), SEWRAR = sewage (Raritan Bay), TREND = monotonic trend variables, DOA = dissolved oxygen (Arthur Kill), DOU = dissolved oxygen (Upper Bay), IMFARM = acreage of improved farmland.

(c) A third hydrographic variable can be entered significantly: addtion of May flow increases the R^2 value to 0.8420.

(d) A significant stock relationship can be obtained with a lag period of 3-8 years. Ages 6-8 generally contribute to the offshore international fishery but generally not to the Hudson River fishery.

(e) A second and a third hydrographic variable can be entered significantly, but only if added together. Neither July flow nor February temperature individually adds significantly to June temperature. The addition of February temperature and July flow together increases the R^2 value to 0.5440.

(f) A third hydrographic variable can be entered significantly: the addition of July temperature increases the R^2 value to 0.7030.

Table 38. (continued

Stock	Model		
	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
<u>Estuarine residents</u>			
White perch	0.0880	0.2145 (April T)	0.3570 (DOH)
Oyster	0.0110 (NS)	0.4830 (August T,F)	0.5348 (SEWRAR)
Hard clam	0.1431	0.7225 (July T) (August T)	None
Soft clam	0.4350	0.6330 (May T) (June T)	0.6701 (TREND) 0.7160 (DOA)
<u>Ocean spawners/estuarine developers</u>			
Blue crab	0.2960	0.3700 (June T)[e]	None
Menhaden	0.1400	0.2540 (June T)	None
Lobster	0.3380	0.6850 (April T)	0.7470 (TREND) 0.7650 (DOU)
Summer flounder	-0.0170 (NS)	None	None
Weakfish	0.5220	0.7460 (May W) (June F)	0.8090 (TOTVOL)
Bluefish	0.2690	0.3640 (June F)	0.4740 (TREND) 0.5220 (TOTVOL) 0.6020 (DOU)
Butterfish	0.0510 (NS)	0.3640 (June T) (July T)	None
EEl	0.3249	0.3985 (June T)	0.5820 (TREND) 0.5040 (TOTVOL) 0.4840 (DOU)
Winter flounder	0.2833	0.3463 (April T)	0.4884 (DOU)
Spot	0.1530	0.2270 (April T)	0.3260 (TOTVOL)

Table 38. (continued

Stock	Model		
	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
<u>Ocean spawners/developers</u>			
Tautog	-0.0150 (NS)	0.3880 (June F) (February T)	0.5400 (TOTVOL)
Scup	0.2510	0.5700 (July W) (September T)[f]	0.7350 (TREND) 0.7270 (TOTVOL) 0.6620 (DOU)

Table 39. Results of categorical time-series regression denoting significant stock, hydrographic, and pollution variables for models which account for greater than 55% of historical variation in the Hudsron-Raritan estuary

Stock	R_2	Main Effects[a]	Interactions[b,c]
Striped bass	.857	Stock	HS-LF4-LT5-HF5
			HS-LF4-HT5-HF5*
American shad	.705	None	HS-HF4-LT4-HDO
			LS-HF4-HT4-HDO
Tomcod	.844	Stock, T1, F4	HS-HT1-LF4-HD*
			HS-HT1-HF4-LD
Soft clam	.716	Sewage	HS-LT5-LT6-LSw
Lobster	.765	None	HS-LT4-LSw*
Hard clam	.723	Stock, T7, T8	HS-HT7-LT8*
Bluefish	.602	F6, Dissolved O_2	HS-LF6-LDO*
Scup	.727	W7	HS-HW7-LT9-LD*
American eel	.582	T6	None

[a] Tx, Fx, and Wx = Water temperature, freshwater disccharge, and wind speed and direction, respectively; x refers to specific calendar months 1 through 12 (e.g., T3 = March temperature). An underscore indicates a positive relationship between predicted stock abundance and the indicated variable(s) for direct effects; no underscore indicates a negative relationship.

[b] The naming convention for interaction terms is as follows: the first character refers to category type (H = High, L = Low); the second character refers to the variable (S = Stock, T = Temperature, F = Flow, W = Wind, Sw = Sewage, DO = Dissolved Oxygen, D = Dreding); the third character refers to calendar months 1 through 12 (e.g., HS-HT8-LT6-HF6 = the interaction among high stock, high August temperature, low June temperature, and high June flow conditions). If no number is included, then the conditions that existed are not month specific (e.g., LSw refers to low annual sewage loading).

[c] Indicates an interaction that produces a contribution to future stock abundance significantly greater (*), or less (no *) than the historical average contribution to stock (t = test; a = 0.5).

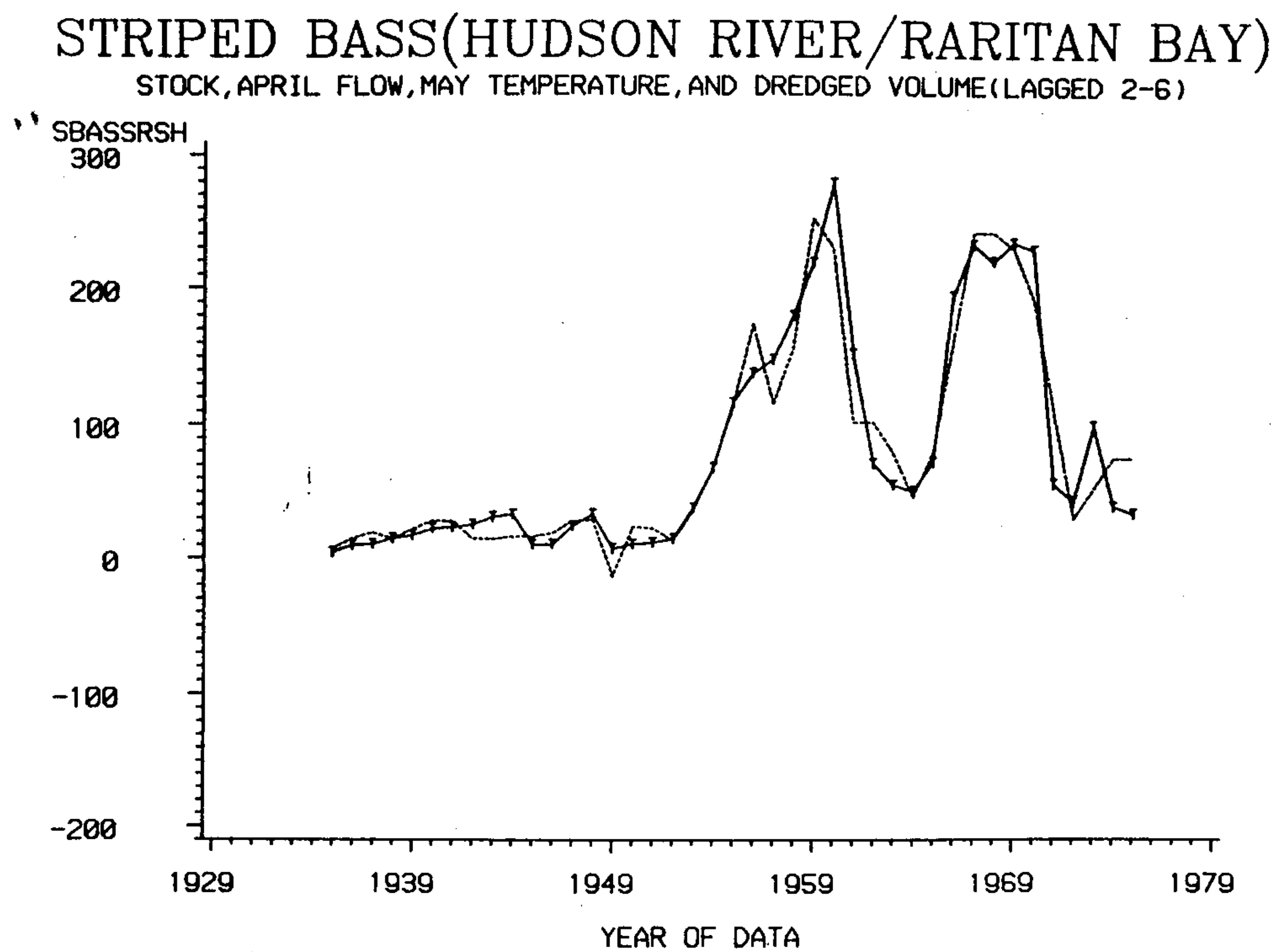

Figure 54. Model of stock variation (1935-1976) for Hudson/Raritan estuary striped bass. Key: T-T = observed, --- = predicted. Stock, April river flow, May temperature, and dredged volume lagged 2-6 years.

Table 40. Effects of climate and macropollution on abundance of striped bass in the Hudson/Raritan estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	-0.0166	---	NS[(a)]
B. Lagged stock May temperture April flow	8	0.7880	B to A	17.41*[(b)]
C. Lagged stock Sewage loading (SEWHUD)	4	0.5166	C to A	7.53*
D. Lagged stock Dredging (VOL40)	4	0.4500	D to A	NS
E. Lagged stock Dissolved oxygen (DOH)	4	0.4810	E to A	NS
F. Lagged stock May temperature April flow Sewage loading (SEWHUD)	16	0.8050	F to B F to C	NS 9.02*
G. Lagged stock April flow May temperature Dredging (VOL40)	16	0.8573	G to B G to D	3.00* 9.79*
H. Lagged stock April flow May temperature Dissolved oxygen (DOH)	16	0.774	H to B H to E	NS 5.35*
I. Lagged stock April flow May temperature May flow	16	0.8421	I to B	2.86*

(a) Model F-value rather than comparative F-value.
(b) * = significant at $\alpha = 0.05$.

The interaction of high stock, low April flow, high May temperature, and high May flow tends to produce significantly greater than average recruitement to future commercial stocks (Table 39).

Variation in American shad stock abundance can be modeled from lagged stock, April flow and temperature, and dredged volume or summertime levels of dissolved oxygen (Fig. 55). Both volume dredged and dissolved oxygen have a strong positive effect on stock abundance, stronger than that of hydrographic factors (Table 41). These two anthropogenic factors appear to be associated with stock abundance in different ways (i.e., they account for different parts of the variation). Unfortunately, the degrees of freedom in the model are not sufficient to permit construction and testing of both macropollution variables as well as stock and hydrographic variables.

The observed decline in hard clam stock abundance in the Hudson/Raritan system was adequately modeled by a combination of lagged stock and hydrographic variables (Fig. 56). No macropollution variables were associated with the stock variation of the hard clam (Table 42). Hard clam abundance is strongly related to previous stock size (positive), July temperature (positive), and August temperature (negative), as shown in Table 39. Soft clam stock abundance likewise declined, but recovered after World War II. The variation in soft clam abundance can best be modeled from lagged stock, May and June temperature, and dissolved oxygen (Fig. 57). The association of soft clam abundance with lagged stock (Table 43) is likely to be related to fishing pressure, but the stock variability is strongly inversely related to sewage loadings (Table 39).

Except in 1950, scup stock in the Hudson/Raritan region varied according to a relatively consistent pattern. The variation can be adequately modeled from lagged stock, July wind speed and direction, September temperature, and dissolved oxygen concentrations or dredged volume (Fig. 58). Hydrographic and anthropogenic factors influence scup stock variation (Table 44), but variation in wind speed and direction over nearly coastal waters in July is strongly related to future stock size. Strong winds promoting shoreward movement of coastal waters contributes heavily to future commercial stock size.

Lobster and weakfish stock abundances in the Hudson/Raritan estuary are well modeled by hydrographic and anthropogenic variables (Figs. 59 and 60), but both of these fisheries have been severely reduced since World War II. As a result, drawing valid conclusions from these two models may be difficult.

Seven of the eight well-modeled stocks in the Hudson/Raritan system are related to at least one anthropogenic factor at least as strongly as to the hydrographic factors (Table 45); only for hard clam are anthropogenic factors not a source of stock variation. Six additional stocks, for a total of 13 of the 19 stocks modeled, could be strongly related to macropollution variables (Table 45).

5.4 Connecticut River

Only one stock, American shad, was evaluated for the Connecticut River; it is the only consistent commercial fishery for this river system. Because this fishery has a long history and has been well studied, we felt that its inclusion in the study would be helpful to the overall objectives of the program. Table 46 lists the lagged stock, hydrographic, and anthropogenic variables used

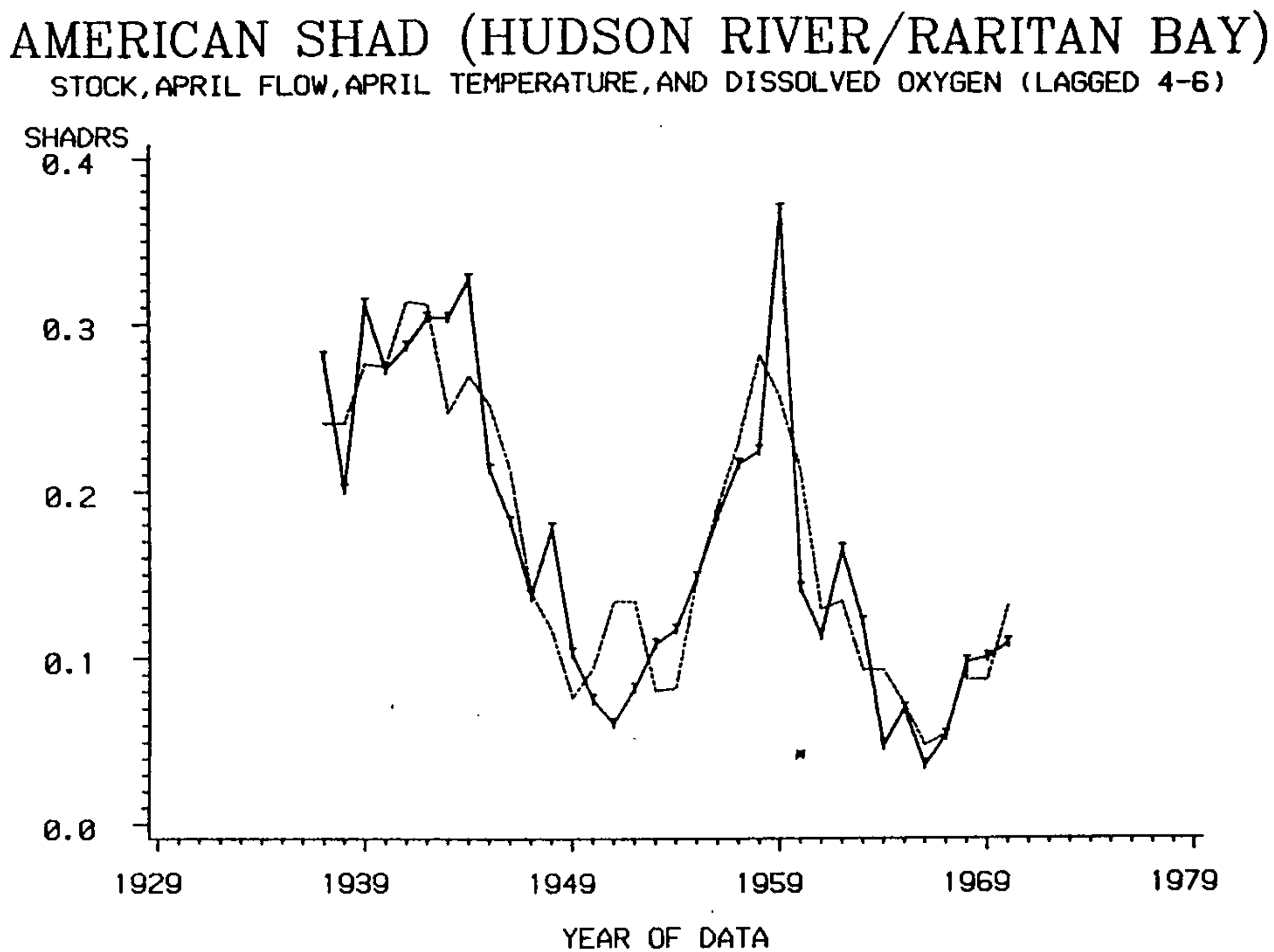

Figure 55. Model of stock variation (1935-1970) in Hudson/Raritan estuary American shad. Key: T-T = observed, --- = predicted. Stock, April river flow, April temperature, and dissolved oxygen lagged 4-6 years.

Table 41. Effects of climate and macropollution on abundance of American shad in the Hudson/Raritan estuary

	Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A.	Lagged stock	2	0.0887	---	4.31*[(a)(b)]
B.	Lagged stock April temperature April flow	8	0.4691	B to A	9.80*
C.	Lagged stock Sewage loading (SEWHUD)	4	0.3533	C to A	7.75*
D.	Lagged stock Dredging (VOL40)	4	0.4044	D to A	9.75*
E.	Lagged stock Dissolved oxygen (DOH)	4	0.1100	E to A	NS
F.	Lagged stock April temperature April flow Sewage loading (SEWHUD)	16	0.3922	F to B F to C	NS NS
G.	Lagged stock April flow April temperature Dredging (VOL40)	16	0.7581	G to B G to D	5.61* 3.83*
H.	Lagged stock April flow April temperature Dissolved oxygen (DOH)	16	0.7050	H to B H to B	5.32* 7.95*

[(a)] Model F-value rather than comparative F-value.
[(b)] * = significant at $\alpha = 0.05$.

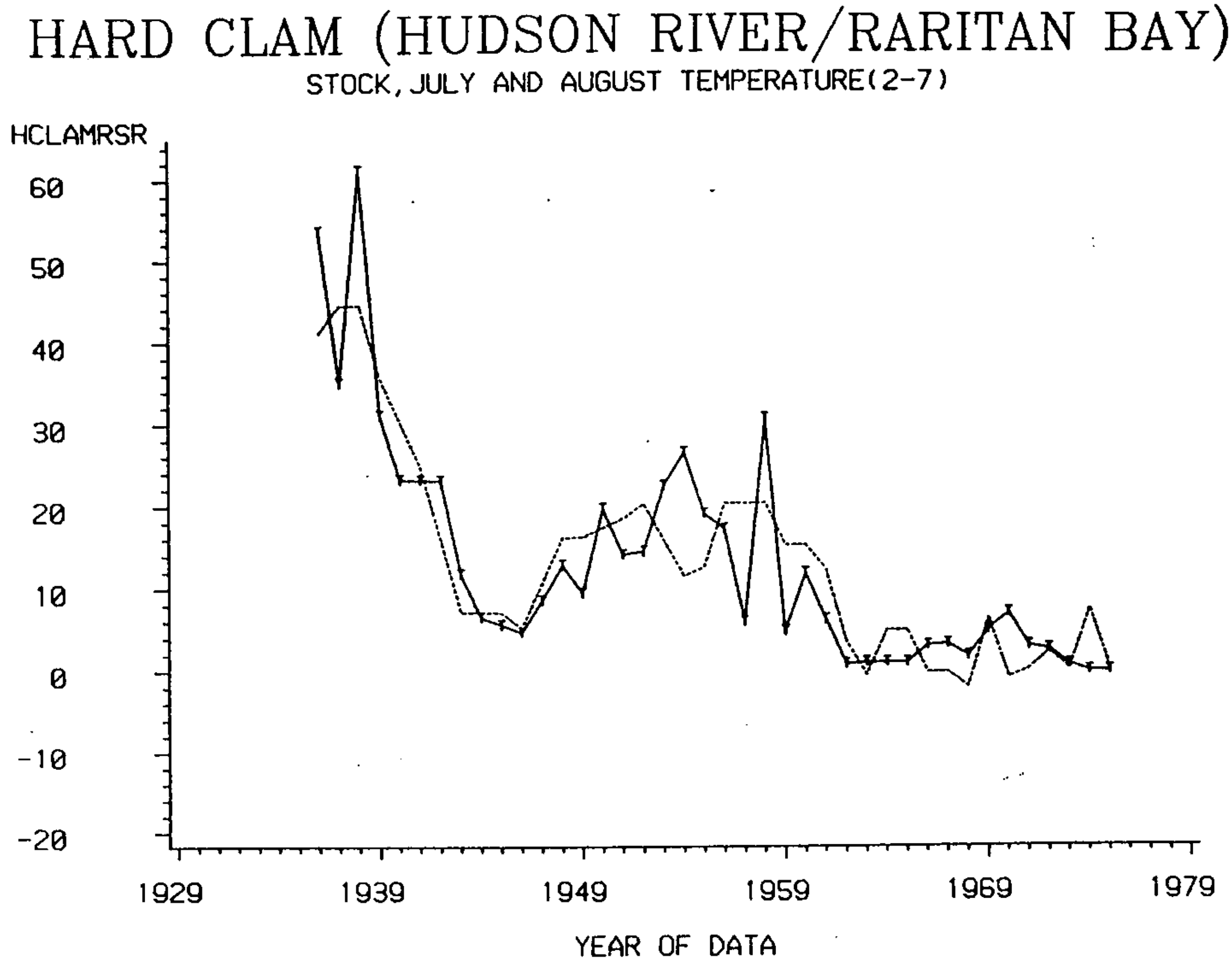

Figure 56. Model of stock variation (1935-1975) in Hudson/Raritan estuary hard clam. Key: T-T = observed, --- = predicted. Stock, July temperature, and August temperature lagged 2-7 years.

Table 42. Effects of climate and macropollution on abundance of hard clam in the Hudson/Raritan estuary

	Regressor Variables	Number of Categories	Adjusted R^2	Comparisons	
				Models	F-Value
A.	Lagged stock	2	0.1431	---	7.51*[(a)]
B.	Lagged stock July temperature August temperature	8	0.7225	B to A	24.09*
C.	Lagged stock Sewage loading (SEWRAR)	4	0.2919	C to A	4.99*
D.	Lagged stock Dredging (TOTVOL)	4	0.1100	D to A	NS
E.	Lagged stock Dissolved oxygen (DOU)	4	0.1450	E to A	NS
F.	Lagged stock July temperature August temperature Sewage loading (SEWRAR)	16	0.7594	F to B F to C	NS 7.36*
G.	Lagged stock July temperature August temperature Dredging (TOTVOL)	16	0.6880	G to B G to D	NS 6.55*
H.	Lagged stock July temperature August temperature Dissolved oxygen (DOU)	16	0.7490	H to B H to E	NS 9.64*

(a) Model F-value rather than comparative F-value.
(b) * = significant at $\alpha = 0.05$.

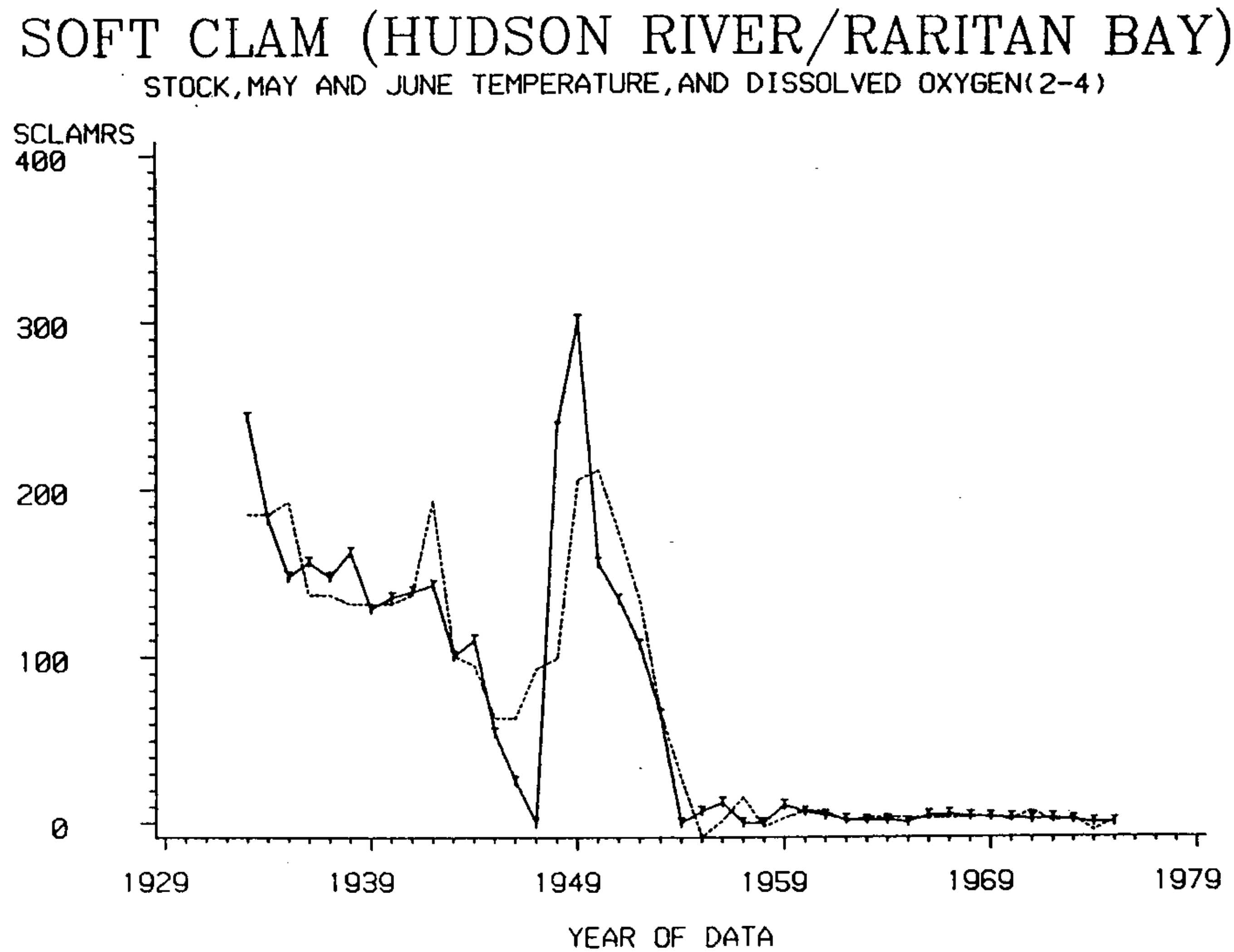

Figure 57. Model of stock variation (1935-1975) in Hudson/Raritan estuary soft clam. Key: T-T = observed, --- = predicted. Stock, May temperature, June temperature, and dissolved oxygen lagged 2-4 years.

Table 43. Effects of climate and macropollution on abundance of soft clam in the Hudson/Raritan estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.4350	---	33.37*[a][b]
B. Lagged stock May temperature June temperature	8	0.6330	B to A	8.67*
C. Lagged stock Sewage loading (SEWRAR)	4	0.4957	C to A	3.46*
D. Lagged stock Dredging (TOTVOL)	4	0.4100	D to A	NS
E. Lagged stock Dissolved oxygen (DOU)	4	0.4610	E to A	NS
F. Lagged stock April temperture April flow Sewage loading (SEWRAR)	16	0.6701	F to B F to C	NS 3.58*
G. Lagged stock April flow April temperature Dredging (TOTVOL)	16	0.6975	G to B G to D	NS 3.77*
H. Lagged stock May temperature June temperature Dissolved oxygen (DOU)	16	0.7161	H to B H to E	2.45* 4.18*

[a] Model F-value rather than comparative F-value.
[b] * = significant at $\alpha = 0.05$.

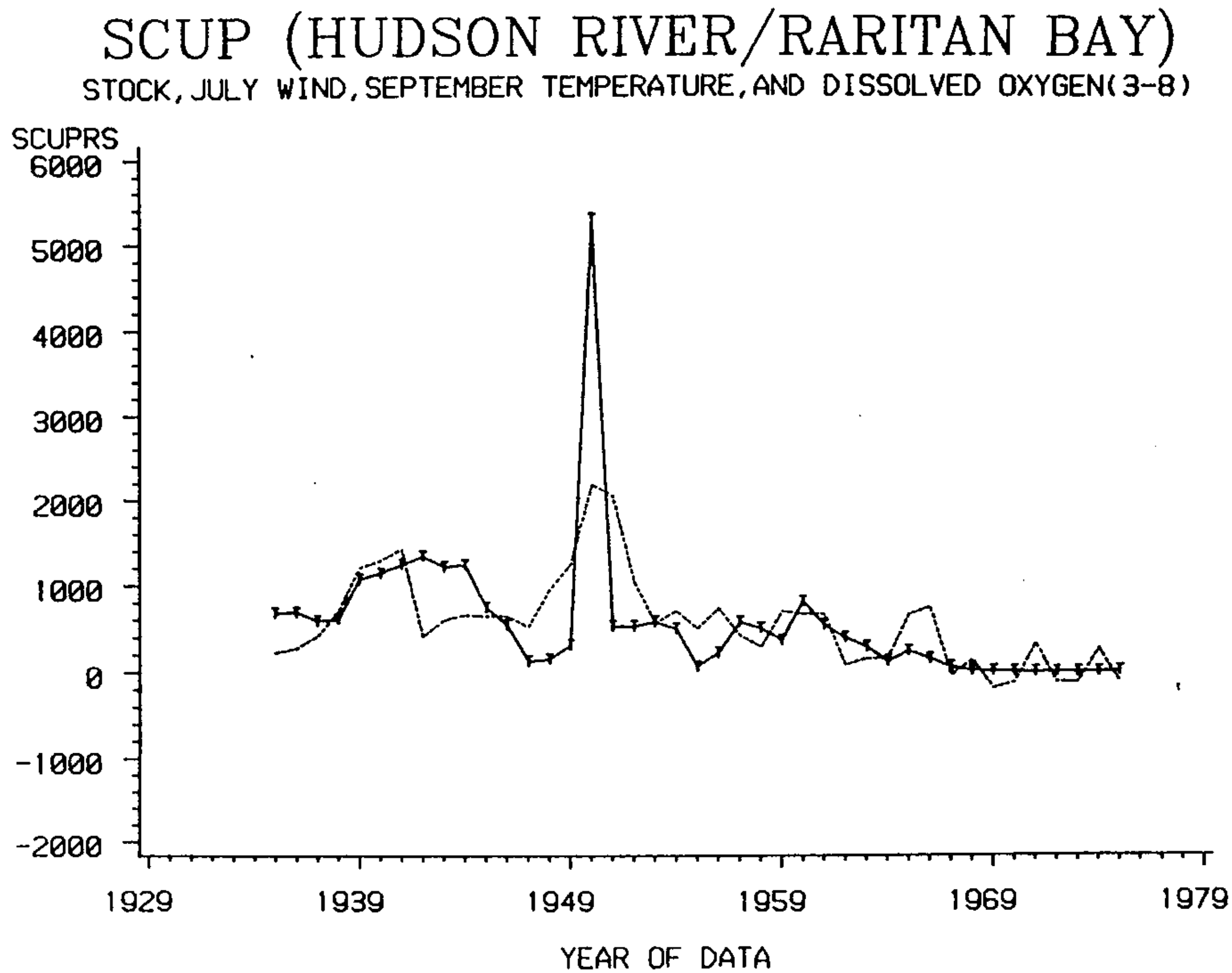

Figure 58. Model of stock variation (1935-1976) in Hudson/Raritan estuary scup. Key: T-T = observed, --- = predicted. Stock, July wind, September temperature, and dissolved oxygen lagged 2-6 years.

Table 44. Effects of climate and macropollution on abundance of scup in the Hudson/Raritan estuary

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons	
			Models	F-Value
A. Lagged stock	2	0.251	---	14.43*[(a)(b)]
B. Lagged stock September temperature July wind	8	0.570	B to A	10.73*
C. Lagged stock Human population (POPULATE)	4	0.377	C to A	4.93*
D. Lagged stock Dredging (TOTVOL)	4	0.402	D to A	5.90*
E. Lagged stock Dissolved oxygen (DOU)	4	0.372	E to A	4.76*
F. Lagged stock September temperature July wind Human population (POPULATE)	16	0.714	F to B F to C	5.19* 6.47*
G. Lagged stock July wind September temperaure Dredging (TOTVOL)	16	0.727	G to B G to D	4.17* 5.41*
H. Lagged stock July wind September temperature Dissolved oxygen (DOU)	16	0.662	H to B H to E	2.50 4.16*

(a) Model F-value rather than comparative F-value.
(b) * = significant at $\alpha = 0.05$.

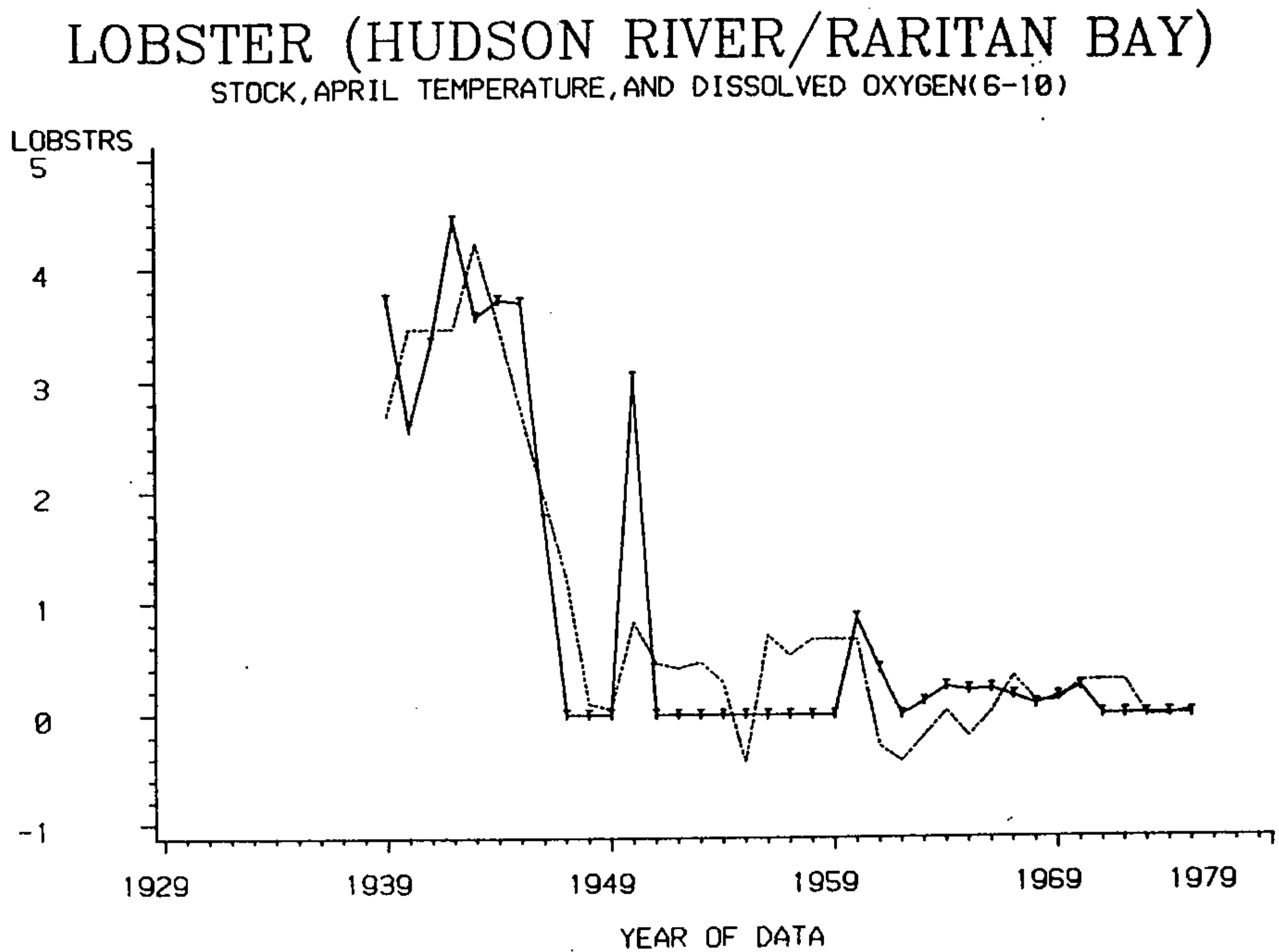

Figure 59. Model of stock variation (1935-1977) in Hudson/Raritan estuary lobster. Key: T-T = observed, --- = predicted. Stock, April temperature, and dissolved oxygen lagged 6-10 years.

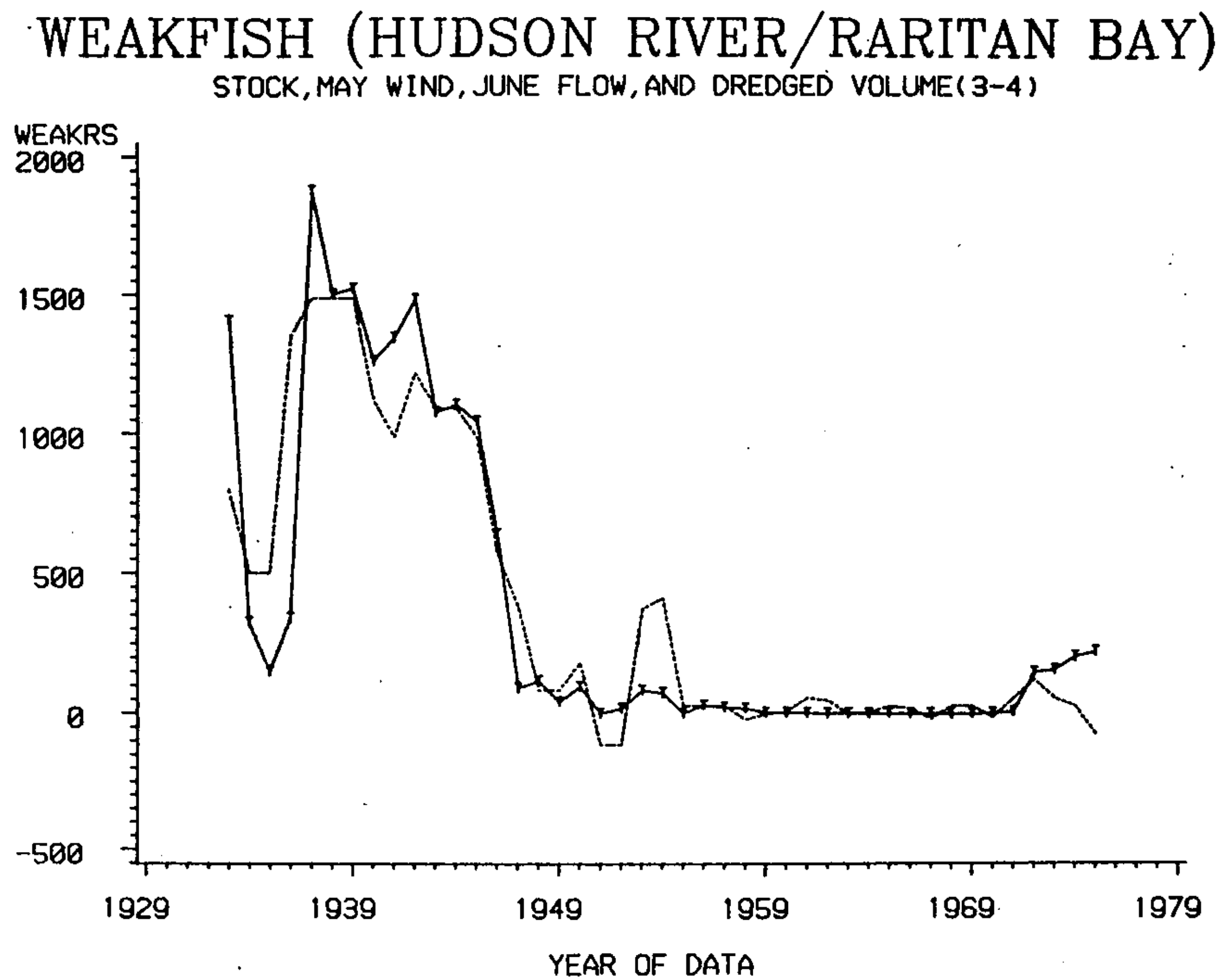

Figure 60. Model of stock variation (1935-1977) in Hudson/Raritan estuary weakfish. Key: T-T = observed, --- = predicted. Stock, June river flow, May wind, and dredged volume lagged 3-4 years.

Table 45. Relative strengths of associations between the stock abundance, climate, and macropollution variables for the Hudson/Raritan estuary[a]

Stock	Macropollution Variables					
	TREND	TOTVOL	DOH	DOU	VOL40	SEWRAR
Striped bass	2	2	2		1	
American shad	4	1	1		1	
Alewife	4	1	2		2	
Sturgeon	4	2	2		4	
Tomcod	2	1	2		1	
White perch	4	4	1			
Oyster	2	2		2		1
Hard clam	2	2		2		2
Soft clam	1	2		1		2
Winter flounder	4	2		3		
Blue crab	4	2		2		
Lobster	1	2		1		
Menhaden	4	4		4		
Weakfish	2	1		2		
Butterfish	4	2		2		
Eel	1	1		1		
Tautog	2	1		2		
Spot	4	1		4		
Scup	1	1		1		

[a] Key:
1 = Both climate and pollution are important.
2 = Climate is more important than pollution.
3 = Pollution is more important than climate.
4 = Second variable is nonsignificant when first variable is significant (potential collinearity of climate and pollution).

Table 46. Lagged variables used in the Connecticut River analysis

Stock	Lag (years)	Variables: Hydrographic[a]	Variables: Anthropogenic[b]
American shad	4-8	April R,T May R,T June R,T	T, TOTVOL

[a] Significant additions to stock model:
R = rainfall.
T = temperature.

[b] Significant additions to stock-climate model:
T = macropollution trend variables (human population).
TOTVOL = dredge volume removed between river miles 0 and 45.

in the analysis. The hydrographic variables were chosen to represent the spawning and early development period of shad in the Connecticut (Werme et al., 1983; DiNardo et al., 1984; Crecco, 1984). Two categories of macropollution variables were analyzed: human population trends (which generally indicate levels of farmland, sewage loading, and employment) and volume of dredged material removed between river miles 0 and 45.

Figure 61 shows the best model fit for American shad stocks in the Connecticut River. The inclusion of June temperature, previous stock levels, and dredging activity can account for 55% of the variation in shad stock abundance. Both the June temperature and the volume dredged from the river are strong determinants of stock abundance (Table 47). The strongest contributor to future stock levels appeared to be the interaction of high stock levels, high June temperature, and high dredging activity.

5.5 Narragansett Bay

Eighteen stocks were evaluated for the Narragansett Bay/Rhode Island Sound region. Table 48 lists the lagged stock, hydrographic, and anthropogenic variables used in the analyses. Hydrographic variables were chosen to represent the spawning and/or developmental period for the stock (Werme et al., 1983; DiNardo et al., 1984; Yetman et al., 1984). The macropollution variables used were human population trends, sewage loading, and volume of material dredged in Narragansett Bay and parts of the Providence, Sakonnet, and Tauton Rivers.

For several species in Narragansett Bay, time-series categorical regression yielded surprisingly good model fits to observed data, given the oceanic nature of the region and the general transitory nature of the fisheries. Models accounting for at least 68% of stock variation were constructed for 6 of the 18 stocks modeled (Table 49); these six stocks were summer flounder (R^2 = 0.89), scup (0.84), winter flounder (0.78), tautog (0.71), bluefish (0.70), and lobster (0.68). An additional three stocks could be modeled to account for at least 55% of stock variation. One stock (windowpane flounder) could not be modeled at all, and abundances of eight stocks were unrelated to anthropogenic variables. Table 50 shows the relationship of future stock sizes in Narragansett Bay to individual variables and combinations of specific categories of these variables.

Summer flounder can best be modeled from lagged stock, June temperature, July river flow, and the sewage loading (Fig. 62). The variables very strongly associated with the abundance of summer flounder in the Narragansett region are the hydrographic and macropollution variables (Table 51). A positive relationship to sewage loading and June temperature as well as an inverse relationship to July flow appears to primarily control stock variability.

Lagged stock, May wind speed and direction, and July temperature best account for the variation in abundance of Narragansett scup (Fig. 63). The observed data are represented well for this fishery without the addition of any macropollution variables (Table 52); in fact, lagged stock and May wind conditions alone can account for 76% of the observed variation. Scup future stock size appears to be directly related to onshore wind speed (i.e., directed

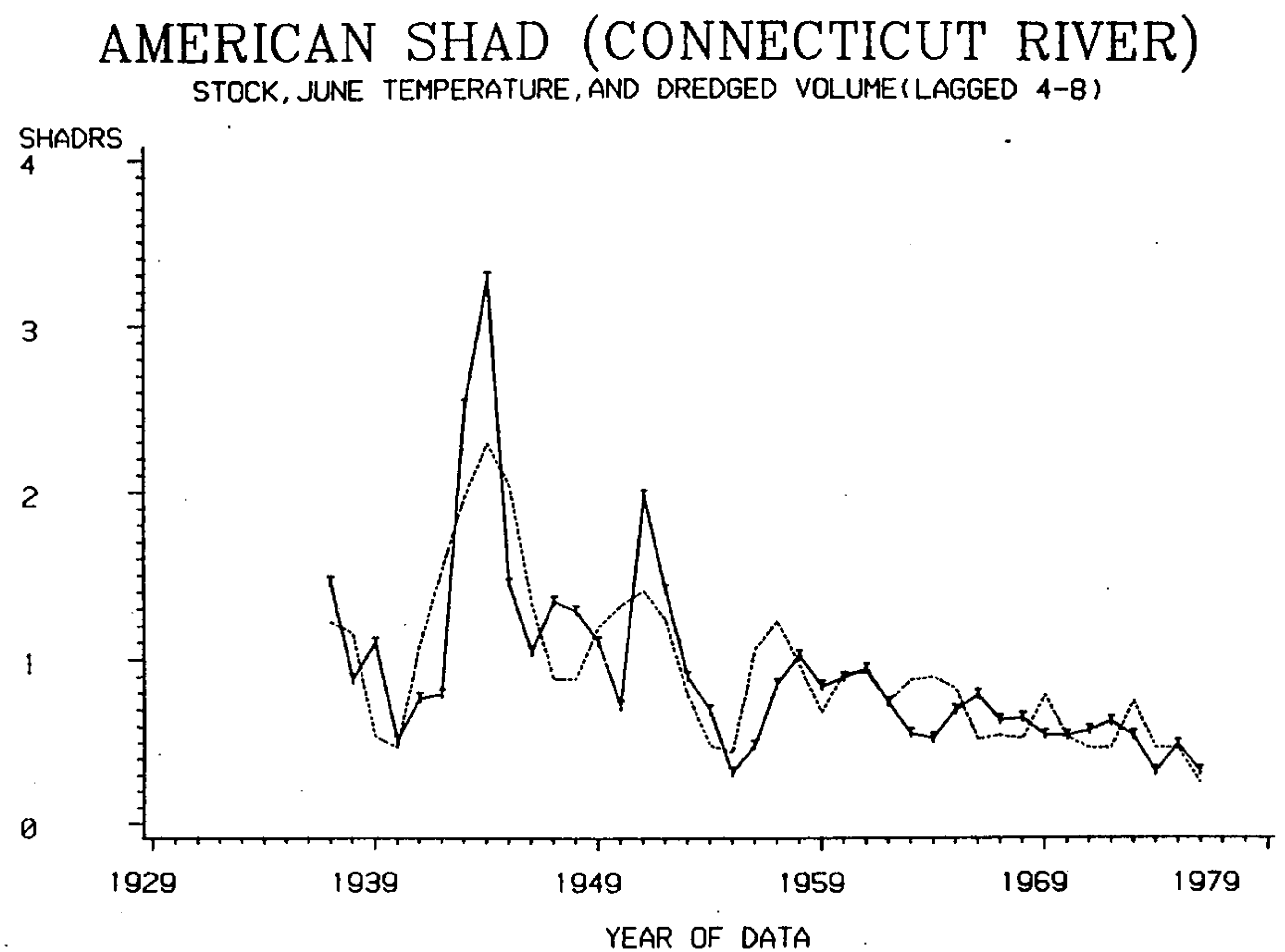

Figure 61. Model of stock variation (1937-1978) in Connecticut River American shad. Key: T-T = observed, --- = predicted. Stock, June temperature, and dredged volume lagged 4-8 years.

Table 47. Effects of climate and macropollution on abundance of American shad in the Connecticut River

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.1086	---	6.24*[(a)(b)]
B. Lagged stock June temperature	4	0.3625	B to A	8.57*
C. Lagged stock Human population (POPULATE)	4	0.1861	C to A	NS
D. Lagged stock Dredging (TOTVOL)	4	0.2723	D to A	5.28*
E. Lagged stock June temperature Human population (POPULATE)	8	0.3109	E to B E to C	NS NS
F. Lagged stock June temperature Dredging (TOTVOL)	8	0.5463	F to B F to D	4.65* 6.44*

[(a)] Model F-value rather than comparative F-value.
[(b)] * = significant at $\alpha = 0.05$.

Table 48. Lagged variables used in Narragansett Bay analyses

Stock	Lag (years)	Variables: Hydrographic[a]	Variables: Anthropogenic[b]
Anadromous species			
Striped bass	4-8	April F,T May F,T June F,T	POP, S, TOTVOL
Smelt	2-3	March F,T April F,T	POP, S, TOTVOL
Alewife	4-5	April F,T May F,T	POP, S, TOTVOL
Estuarine residents			
White perch	3-8	April F,T May F,T	POP, S, TOTVOL
Oyster	4-8	May F,T June F,T July F,T August F,T	POP, S, TOTVOL
Hard clam	3-8	June F,T July F,T August F,T	POP, S, TOTVOL
Soft clam	3-8	June F,T July F,T August F,T	POP, S, TOTVOL
Ocean spawners/estuarine developers			
Lobster	6-10	January T,F February T,F March T,W,F	POP, S, TOTVOL

(a) F = flow.
T = temperature.
W = wind.

(b) POP = human population.
S = sewage loading.
TOTVOL = dredged volume.

Table 49. Results (R^2 values) of the Narragansett Bay analyses

Stock	Model		
	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
Anadromous species			
Striped bass	-0.0050 (NS)	0.1021 (May T)	0.3797 (TREND)
Smelt	0.0000 (NS)	0.1104 (April T)	None
Alewife	-0.0180 (NS)	0.1934 (April T)	None
Estuarine residents			
White perch	0.0664	None	0.3001 (TREND)
Oyster	0.0680 (NS)	0.2970 (May T)	None
Hard clam	0.1795	0.3032 (July F)	None
Soft clam	-0.0108 (NS)	0.0971 (July T)	0.2589 (TOTVOL)
Ocean spawners/estuarine developers			
Menhaden	0.3114	0.5451 (October W) (November W)	None
Winter flounder	0.3441	0.6558 (March F) (March T)	0.7757 (TREND)
Lobster	0.1986	0.4810 (March T)	0.6806 (TREND)
Windowpane flounder	-0.1064 (NS)	None	None
Summer flounder	-0.0078 (NS)	0.4111 (June T) (July F)	0.8921 (TREND) 0.7055 (TOTVOL)[c]

[a] Significant additions to the stock alone model. Key: F = river flow, T = temperature, W = wind.

[b] Significant additions to the best stock-hydrographic model. Key: TREND = monotonic trend variable, TOTVOL = dredging activity.

[c] A model that includes two macropollution variables (human population and dredging) and no hydrographic variables is significant, $R^2 = 0.8684$.

Table 49. (continued)

Stock	Model		
	Stock Alone	Hydrographic Variables[a]	Anthropogenic Variables[b]
Weakfish	0.1771	0.3232 (July T)	0.4847 (TREND)
Bluefish	0.3461	0.7034 (August T)	None
Eel	0.2823	0.4251 (March T)	0.6079 (TREND)
Butterfish	0.1523	0.5501 (June T) (July W)	None
<u>Ocean spawners/developers</u>			
Scup	0.5354	0.8398 (May W) (July T)	None
Tautog	0.4399	0.5137 (June F)	0.7086 (TREND)

Table 50. Results of categorical time-series regression denoting significant stock, hydrographic, and pollution variables for models which account for greater than 55% of historical variation in Narragansett Bay

Stock	R^2	Main Effects[a]	Interactions[b,c]
Lobster	.681	None	HS-HT3-HSw
Summer flounder	.892	T6, F7, Sewage	None
Scup	.840	Stock, W5, T7	HS-LW5-HT7
			HS-HW5-HT6*
Winter flounder	.776	Stock, T3	HS-LF3-LT3-HW2
			HS-LF3-HT3-HW2*
			HS-HF3-HT3-LW2
Bluefish	.703	Stock, T8	HS-HT8*
American eel	.608	T3, Sewage	None

(a) Tx, Fx, and Wx = Water temperature, freshwater discharge, and wind speed and direction, respectively; x refers to specific calendar months 1 through 12 (e.g., T3 = March temperature). An underscore indicates a positive relationship between predicted stock abundance and the indicated variable(s) for direct effects; no underscore indicates a negative relationship.

(b) The naming convention for interaction terms is as follows: the first character refers to category type (H = High, L = Low); the second character refers to the variable (S = Stock, T = Temperature, F = Flow, W = Wind, Sw = Sewage, DO = Dissolved Oxygen, D = Dredging); the third character refers to calendar months 1 through 12 (e.g., HS-HT8-LT6-HF6 = the interaction among high stock, high August temperature, low June temperature, and high June flow conditions). If no number is included, then the conditions that existed are not month specific (e.g., LSw refers to low annual sewage loading).

(c) Indicates an interaction that produces a contribution to future stock abundance significantly greater (*), or less (no *) than the historical average contribution to stock (t = test, a = 0.5).

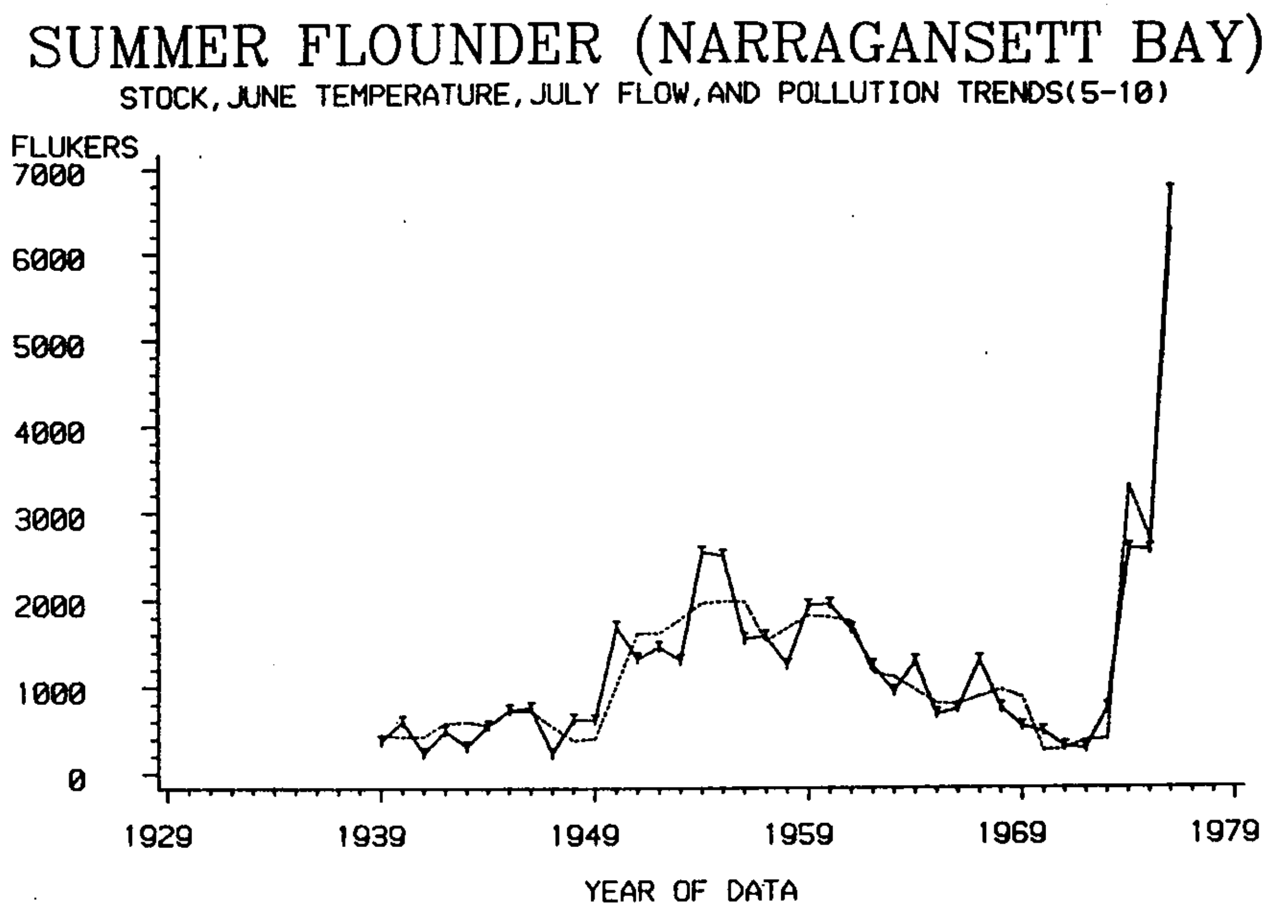

Figure 62. Model of stock variation (1939-1974) in Narragansett Bay summer flounder. Key: T-T = observed, --- = predicted. Stock, July river flow, June temperature, and human population lagged 5-10 years.

Table 51. Effects of climate and macropollution on abundance of summer flounder in the Narragansett Bay

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.0078	---	NS[a]
B. Lagged stock June temperature July flow	8	0.4111	B to A	11.21*[b]
C. Lagged stock Sewage	4	0.5444	C to A	22.81*
D. Lagged stock Dredging (TOTVOL)	4	0.2603	D to A	7.52*
E. Lagged stock June temperature July flow Sewage	16	0.8921	E to B E to C	25.75* 13.17*
F. Lagged stock July flow June temperature Dredging (TOTVOL)	16	0.7055	F to B F to D	8.64* 8.01*
G. Lagged stock Sewage Dredging (TOTVOL)	8	0.8684	G to C G to D	21.93* 40.27*

[a] Model F-value rather than comparative F-value.
[b] * = significant at α = 0.05.

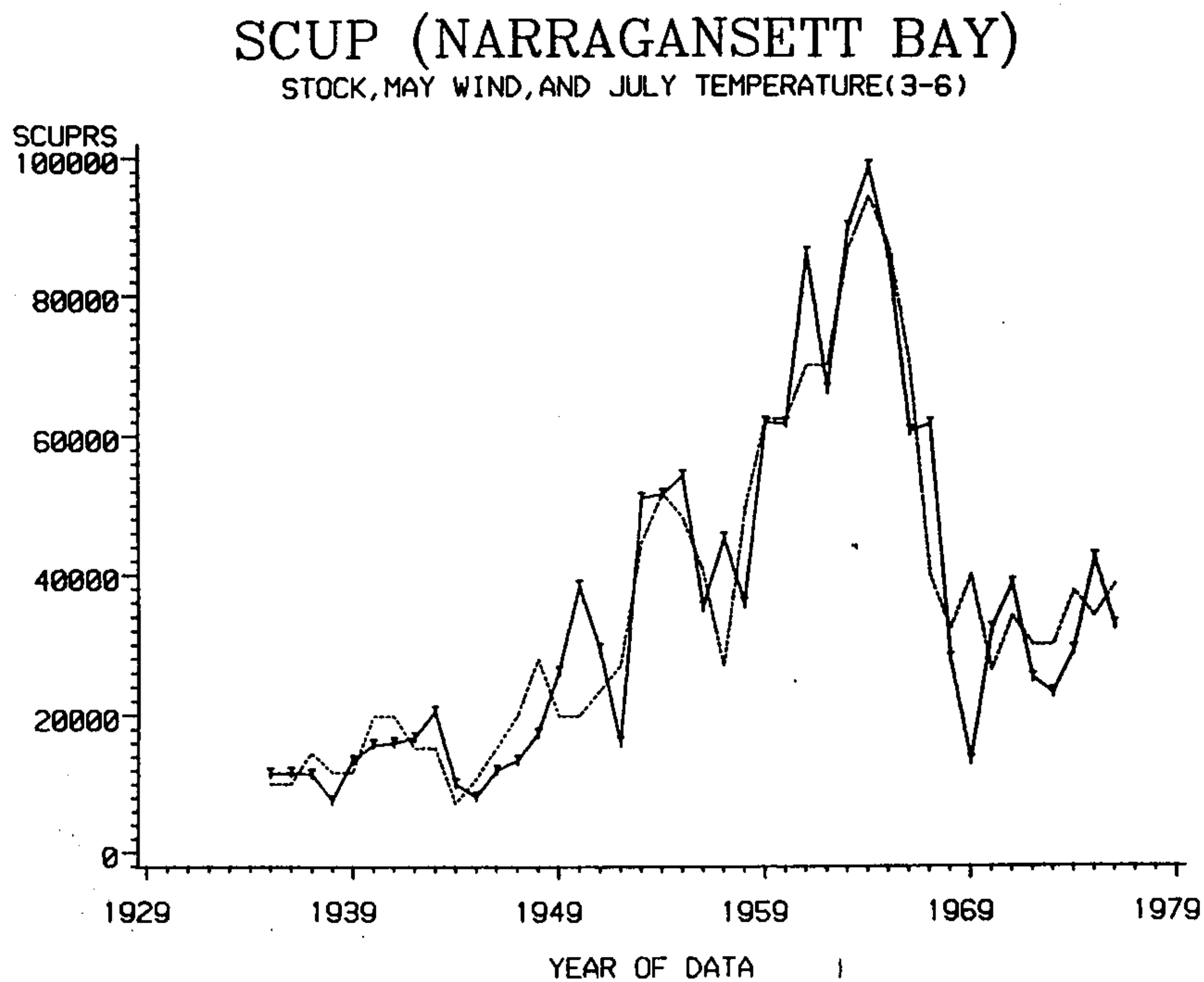

Figure 63. Model of stock variation (1935-1974) in Narragansett Bay scup. Key: T-T = observed, --- = predicted. Stock, May wind, and July temperature lagged 3-6 years.

Table 52. Effects of climate and macropollution on abundance of scup in the Narragansett Bay

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.5354	---	49.88*(a,b)
B. Lagged stock July temperature May wind	8	0.8398	B to A	24.68*
C. Lagged stock Sewage	4	0.5245	C to A	NS
D. Lagged stock Dreding (TOTVOL)	4	0.5382	D to A	NS
E. Lagged stock July temperature May wind Sewage	16	0.8274	E to B E to C	NS 7.67*
F. Lagged stock May wind July temperatue Dredging (TOTVOL)	16	0.8395	F to B F to D	NS 7.48*

(a)Model F-value rather than comparative F-value.
(b)* = significant at $\alpha = 0.05$.

onshore) and July temperature. High values for both of these variables combined with high stock levels tend to produce significantly larger than average future recruitments to commercial stocks (Table 50).

Tautog is a Narragansett Bay/Rhode Island Sound fishery that is well modeled from both hydrographic and anthropogenic variables (Fig. 64). Lagged stock, June river flow, and the macropollution trend variable account for 71% of the variation in this stock from 1933 to 1978. Stock variation is negatively related to sewage loadings. Both hydrographic and anthropogenic factors contribute equally to the explanation of variation in abundance of tautog (Table 53).

Relative stock abundance of winter flounder increased significantly from 1950 to 1970 in the Narraganset region and then decreased from 1970 to 1977 (Fig. 65). A model including the categorical variables, lagged stock, March temperature, and March river flow, plus sewage loading, fits this pattern and can account for 78% of the observed variation in stock abundance. This stock is strongly associated with hydrographic variables (Tables 54 and 50).

Stock abundance of lobster in the Narragansett region, like that of winter flounder, increased from 1950 to 1970 and then decreased (Fig. 66). Late-winter hydrographic conditions (March river flow and temperature) alone can account for a significant part of stock variation and, with the addition of lagged stock and human population, can account for 68% of the variation in stock abundance. Both anthropogenic and hydrographic factors are strongly associated with lobster stock abundance (Table 55); anthropogenic factors are positively related to abundance and may reflect changes in fishing pressure.

Bluefish harvests in the Narragansett region were relatively small until 1960 but have steadily increased since then. Lagged stock and August temperature can be used to adequately model ($R^2 = 0.73$) bluefish stock abundance (Fig. 67). No anthropogenic factor tested was significantly related to variation in bluefish abundance (Table 56).

For 8 of the 16 stocks for which the relative strengths of anthropogenic and hydrographic factors could be compared, anthropogenic variables were at least as important as hydrographic conditions in determining stock abundance (Table 57). In only two (i.e., scup and bluefish) of the six well-modeled Narragansett stocks ($R^2 \geq 0.68$) were anthropogenic influences not a major source of variation.

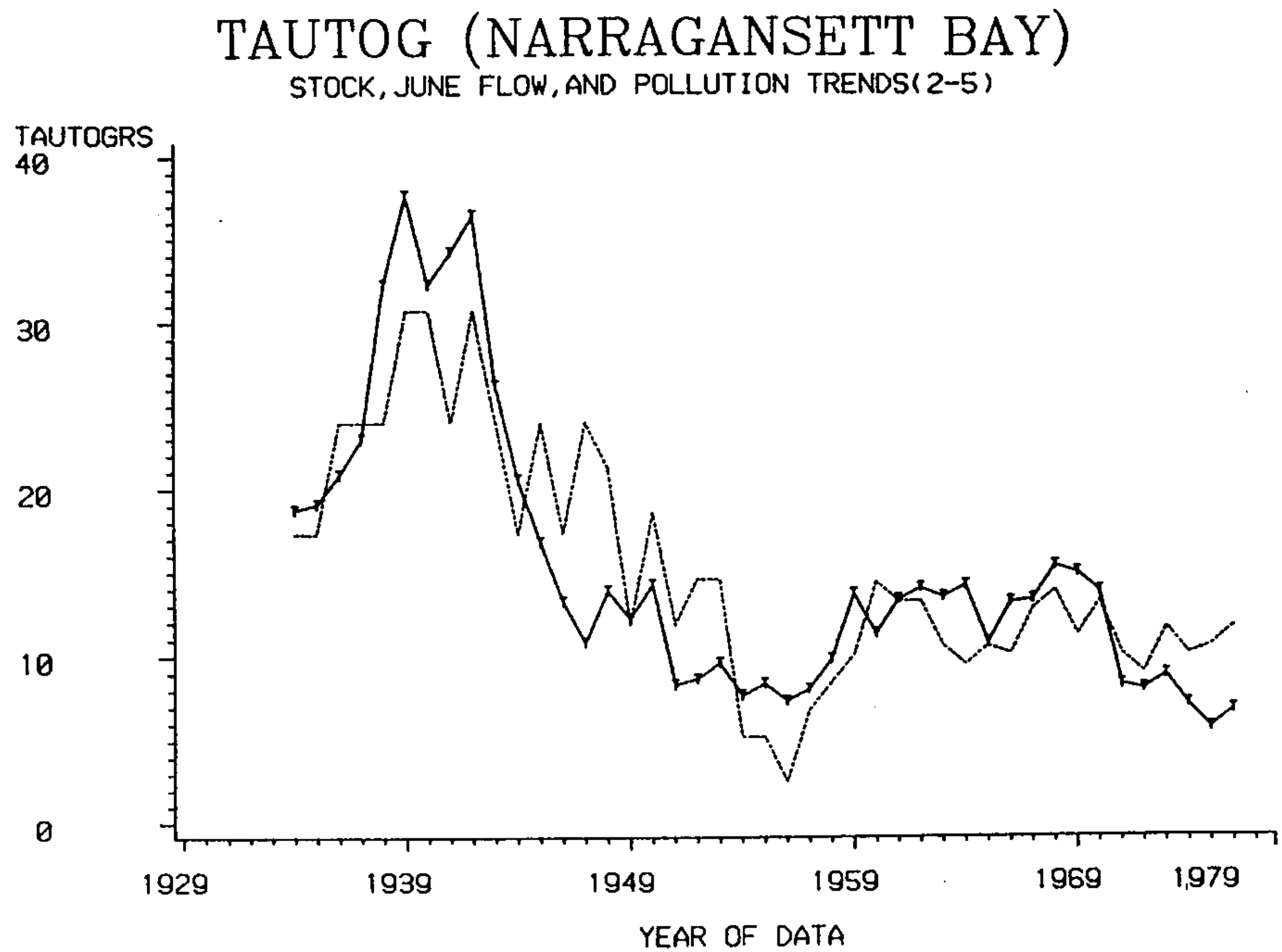

Figure 64. Model of stock variation (1935-1977) in Narragansett Bay tautog. Key: T-T = observed, --- = predicted. Stock, June river flow, and sewage loadings lagged 2-5 years.

Table 53. Effects of climate and macropollution on abundance of tautog in the Narragansett Bay

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons	
			Models	F-Value
A. Lagged stock	2	0.4399	---	33.99*[a,b]
B. Lagged stock June flow	4	0.5137	B to A	4.11*
C. Lagged stock Sewage	4	0.5528	C to A	6.17*
D. Lagged stock Dredging (TOTVOL)	4	0.4515	D to A	NS
E. Lagged stock June flow Sewage	8	0.7086	E to B E to C	4.81* 3.72*
F. Lagged stock June flow Dredging (TOTVOL)	8	0.5353	F to B F to D	NS 2.76*

[a] Model F-value rather than comparative F-value.
[b] * = significant at $\alpha = 0.05$.

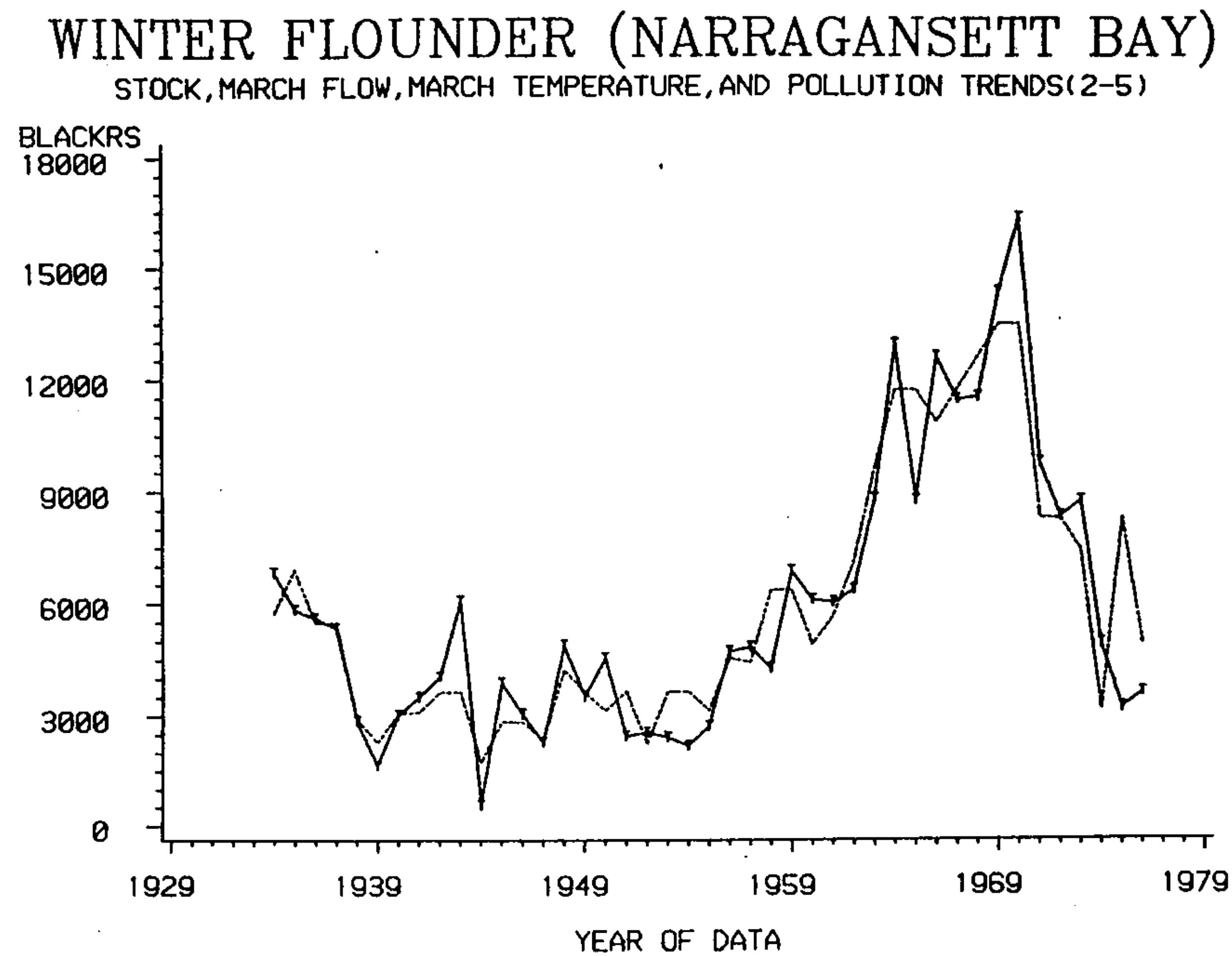

Figure 65. Model of stock variation (1933-1974) in Narragansett Bay winter flounder. Key: T-T = observed, --- = predicted. Stock, March river flow, March temperature, and human population lagged 2-5 years.

Table 54. Effects of climate and macropollution on abundance of winter flounder in the Narragansett Bay

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.3441	---	23.04*[(a,b)]
B. Lagged stock March temperature March flow	8	0.6558	B to A	13.88*
C. Lagged stock Sewage	4	0.5525	C to A	10.55*
D. Lagged stock Dredging (TOTVOL)	4	0.3149	D to A	NS
E. Lagged stock March temperature March flow Sewage	16	0.7757	E to B E to C	3.67* 4.53*
F. Lagged stock March flow March temperature Dredging (TOTVOL)	16	0.6746	F to B F to D	NS 4.59*

[(a)]Model F-value rather than comparative F-value.
[(b)]* = significant at $\alpha = 0.05$.

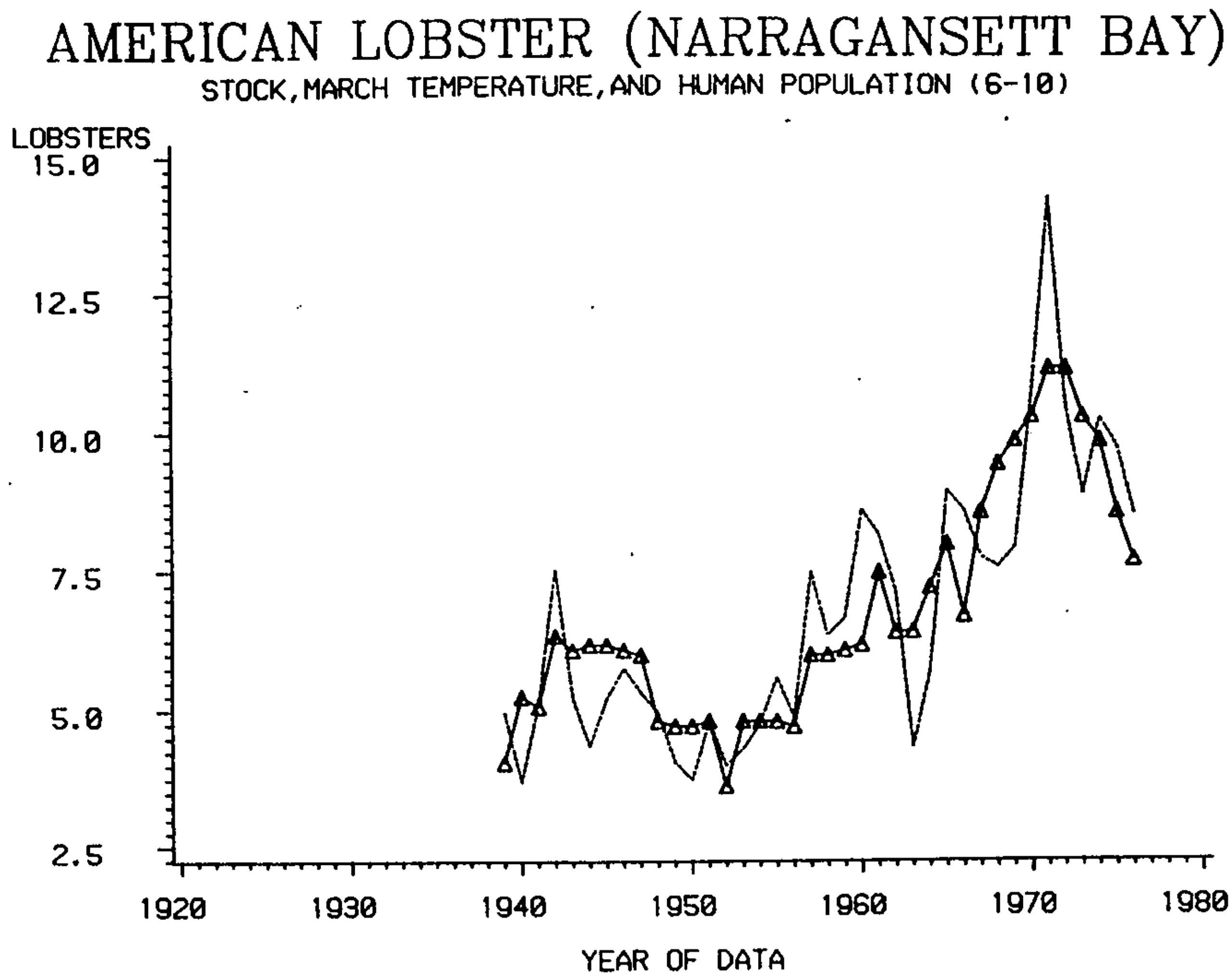

Figure 66. Model of stock variation (1938-1977) in Narragansett Bay lobster. Key: T-T = observed, --- = predicted. Stock, March temperature, and human population lagged 6-10 years.

Table 55. Effects of climate and macropollution on abundance of lobster in the Narragansett Bay

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.1986	---	10.44*[(a)(b)]
B. Lagged stock March temperature	4	0.4810	B to A	10.27*
C. Lagged stock Human population (POPULATE)	4	0.5525	C to A	15.23*
D. Lagged stock Dredging (TOTVOL)	4	0.2858	D to A	NS
E. Lagged stock March temperature Human population (POPULATE)	8	0.6806	E to B E to C	6.31* 4.41*
F. Lagged stock March temperature Dredging (TOTVOL)	8	0.4803	F to B F to D	NS 4.18*

(a) Model F-value rather than comparative F-value.
(b) * = significant at $\alpha = 0.05$.

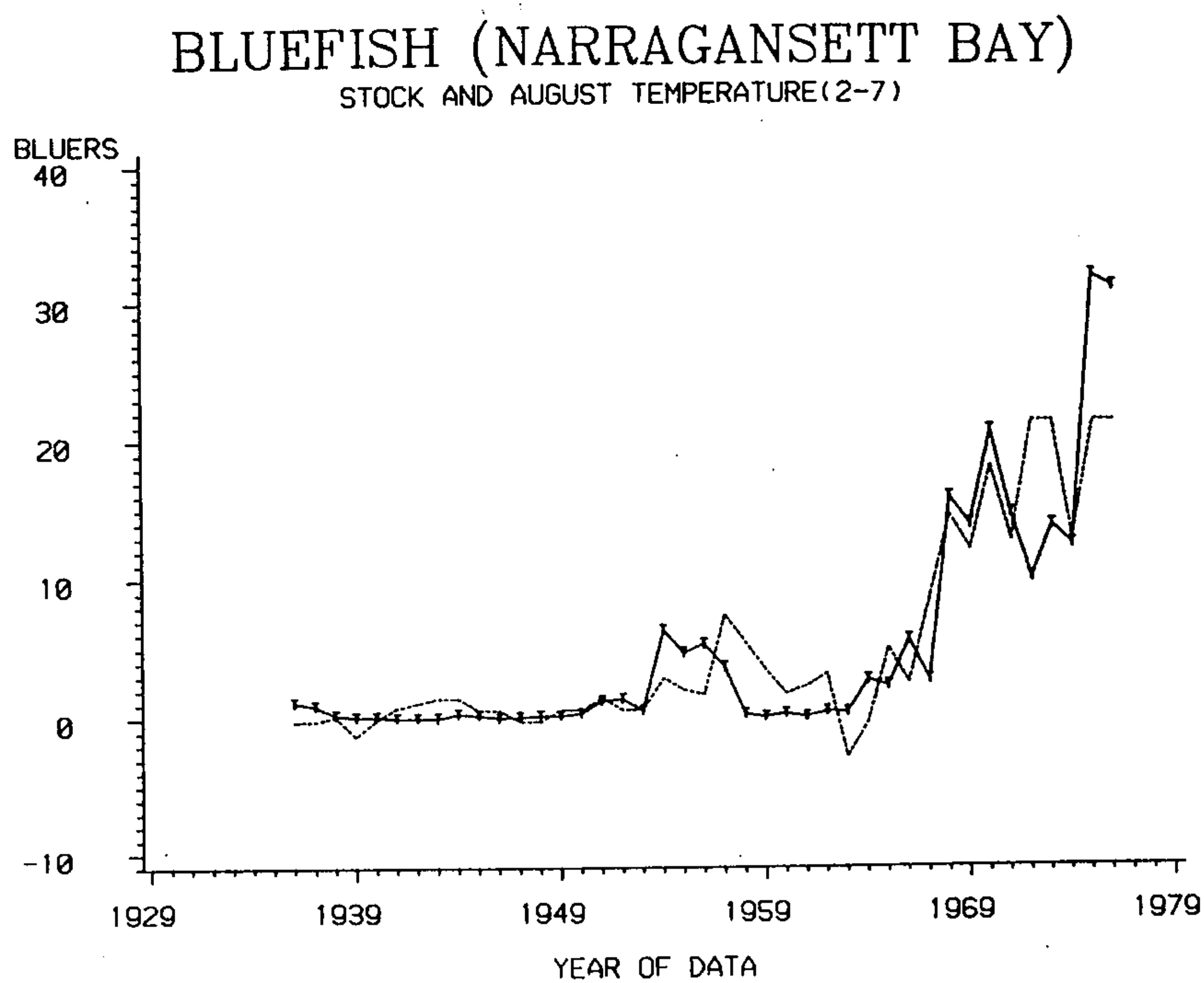

Figure 67. Model of stock variation (1937-1977) in Narragansett Bay bluefish. Key: T-T = observed, --- = predicted. Stock and August temperature lagged 2-7 years.

Table 56. Effects of climate and macropollution effects on abundance of bluefish in the Narragansett Bay

Regressor Variables	Number of Categories	Adjusted R^2	Comparisons: Models	Comparisons: F-Value
A. Lagged stock	2	0.3461	---	22.17*[a,b]
B. Lagged stock April temperature	4	0.7034	B to A	24.50*
C. Lagged stock Human population (POPULATE)	4	0.5763	C to A	11.59*
D. Lagged stock Dredging (TOTVOL)	4	0.3390	D to A	NS
E. Lagged stock August temperature Human population (POPULATE)	8	0.7304	E to B E to C	NS 6.29*
F. Lagged stock August temperature Dredging (TOTVOL)	8	0.6860	F to B F to D	NS 11.22*

[a] Model F-value rather than comparative F-value.
[b] * = significant at α = 0.05.

Table 57. Relative strengths of associations between stock abundance, climiate, and macropollution variables for the Narragansett Bay[a]

Stock	Macropollution Variables		
	POPULATE	SEWAGE	TOTVOL
Striped bass	1	1	4
Smelt	2	2	4
Alewife	2	2	2
White perch[b]			
Oyster	2	2	2
Hard clam	4	4	2
Lobster	1	1	4
Soft clam	4	4	1
Menhaden	2	2	2
Weakfish	3	3	2
Bluefish	2	2	2
Eel	1	1	2
Summer flounder	1	1	1
Tautog	1	1	2
Winter flounder	1	1	2
Butterfish	2	2	2
Scup	2	2	2
Windowpane flounder[b]			

(a) Key:

1 = Both climate and pollution are important.
2 = Climate is more important than pollution.
3 = Pollution is more important than climate.
4 = Second variable is nonsignificant when first variable is significant (potential collinearity of climate and pollution).

(b) No significant models could be constructed.

6. DISCUSSION AND INTERPRETATION

In the most ideal case, an analysis scheme such as that portrayed in Chapters 4 and 5 would consistently provide results indicating that there were significant relationships between anthropogenic variables and stock abundance in relatively "polluted" estuaries and no such relationships in relatively "unpolluted" estuaries. Unfortunately, to make true comparisons across estuaries, this statistical approach must assume that all other factors except pollution are constant. Climatic factors, physical and hydrographic conditions, and even stock patterns are obviously not similar across estuaries; and upon close inspection, one really would not expect that comparisons could be easily and consistently made among estuaries. The stocks display latitudinal gradients in which target estuaries sometimes represent the limits of their distribution (e.g., spot in the Hudson-Raritan Estuary). Also, the physical characteristics of the target estuaries are somewhat different. For example, the rapid flushing of the Narragansett Bay estuary due to tidal action easily disperses large pollutant inputs. In addition, pollutant inputs to the "polluted" estuaries can potentially have different origins. Thus, one cannot expect a priori to find consistent relationships between fishery stocks and particular pollution sources (e.g., copper, PCB).

Each of the fisheries groups -- anadromous, resident, ocean/estuarine, and ocean -- will be discussed individually. The primary purposes of the interpretive discussion are:

- To examine the significant correlations and evaluate whether they can be interpreted as having a relationship to the stocks' biological and life history characteristics and whether those correlations are consistent with findings reported in the established scientific literature, and
- To develop rigorous hypotheses, where warranted, that describe stock dynamics in relation to natural hydrographic conditions and/or anthropogenic influences.

6.1 Anadromous Fisheries

In general, the major anadromous fisheries of the mid-Atlantic region -- American shad and striped bass -- can be modeled well by the categorical, time-series regression approach. Results of analyses of stocks of these species across estuaries appear to be strongly supported by the models and appear consistent primarily because these species spawn and develop in the freshwater/oligohaline reaches of the target estuaries and are thus continually exposed to the specific hydrographic conditions within each estuary during their early life stages. In addition, there have historically been fisheries directed at landing these species, which suggests that one can support the concept of using records of landings and fishing effort to estimate relative abundance. On the other hand, results of analyses of alewife and blueback herring are highly variable. However, the landings of these species are often bycatches of other fisheries, making the use of catch and effort records a more questionable measure of true stock abundance.

6.1.1 American shad

Consistent with results reported in much of the literature (e.g., Crecco, 1983; Chittenden, 1975), our analyses of American shad displayed low but significant lagged stock relationships ($R^2 < 0.10$) in all estuaries except the Potomac River, where the lagged relative stock measure accounted for 33% of historical variance in stock abundance. The low but significant figures suggest that the year-class strength of American shad in northeastern estuaries may be influenced by spawning success but that the magnitude of that influence may be governed by rates of mortality suffered by larvae and young-of-the-year as they pass seaward through regions with poor water quality (Chittenden, 1975) or through obstructions (Leggett, 1969, 1976). In all river systems that we tested, except the Potomac River, American shad larvae historically (1929-1970) have had to pass through regions of poor water quality (e.g., low dissolved oxygen) or had their migrations blocked by dams.

Hydrographic conditions play an important role in the variability of American shad stocks in all the tested estuaries. The relationship between the size of these stocks and these variables (e.g., freshwater discharge, temperature) portrays a reasonable longitudinal pattern from the Potomac River (characterized by March conditions) to the Connecticut River (characterized by June conditions). The significant relationships found between fishable stock size and spring river discharge during spawning, and between fishable stock size and temperature conditions during development, correspond to those described by other investigators (Crecco, 1984; Fredin, 1954). In contrast, Talbot (1954) could not extract significant relationships of stock size to streamflow or temperature for the Hudson River American shad, while the results of this study showed a significant relationship of shad stock size to both April river discharge and April temperature, which accounted for approximately 40% of stock variability. As both data sets were ostensibly the same, this difference must be accredited to different analytical techniques.

A significant positive relationship between general water quality (as characterized by dissolved oxygen concentrations) and the abundance of American shad stocks was determined at all estuaries for which data were available. (No dissolved-oxygen time-series data were available for the Connecticut River.) While these relationships do not allow one to determine the sources influencing water quality (e.g., sewage, industrial, or non-point sources), they do provide evidence of a potential link between water quality or gross pollution and stock abundance of American shad in three major Northeastern estuaries. The evidence for a link is consistent with conjectures made by other investigators (Chittenden, 1974, 1975) and is inconsistent with the results of linear regressions performed by Talbot (1954) and Burdick (1954) to determine relationships of Hudson shad stocks to dissolved oxygen conditions. In the present stuudy, dissolved oxygen levels could be linked significantly to the Hudson River shad stocks only after removing the stock variability due to natural hydrographic conditions (see Table 41). Both Burdick (1954) and Talbot (1954) examined direct relationship between stock size and dissolved oxygen.

Sewage loadings (as described by a simple increasing monotonic trend) are adversely related to shad stock abundance in the Potomac River. Sewage loading certainly affects dissolved oxygen levels, and these loadings in the Potomac River increased drastically from 1929 to 1980 with few changes in Treatment level until the early 1960's (see Chapter 2). The categorization of time-series data for dissolved oxygen levels and treated sewage levels (BOD, or biological oxygen demand) in the Potomac are lagged mirror images of each other. Sewage disposal had overtaxed the Hudson and Delaware basins' capacity to assimilate organic matter by 1929 (Talbot, 1954; Federal Works Agency, 1939; Kiry, 1974), and thus, appears to have had little effect on dissolved oxygen concentrations since that time. It does not seem unreasonable that no relationship was found between stock abundance and sewage loadings in the Delaware or Hudson-Raritan estuaries.

The volume of dredged materials within the spawning reach of American shad was positively associated with stock size in the Connecticut River and weakly associated with stock size in the Hudson River. Talbot (1954) suggested a positive effect of dredging activity on the size of shad stocks in the Hudson, but did not support this implication other than to state that he found no measurable adverse effect on abundance. The reasons for finding a consistently positive but weak relationship between the volume of dredged material and American shad stock size in two major estuaries is elusive. Several possibilities are that dredging may alter local flow or circulation patterns (Talbot, 1954), may create new habitat, may remove oxygen-demanding materials, or may increase nutrient levels and thus eventually increase food supplies (Jones and Lee, 1981).

The abundance of American shad stocks in all target estuaries appears to be related to degraded water quality (low dissolved oxygen).

6.1.2 Striped bass

The striped bass fishery is known to be year-class dominated (Cooper and Polgar, 1981). The models proposed in this report confirm this observation in all estuaries except, seemingly, the Potomac River, where 33% of the variation in striped bass stock can be explained by a lagged stock variable. However, the year-class phenomenon coupled with the multiple-lag structure required to represent 2- to 5-year-old males as well as 4- to 6-year-old returning females result in a type of moving-average value that has some autocorrelative power. Thus, the high value shown in the Potomac for lagged stock is the result of year classes that generally fall 2-6 years apart in the time series rather than the result of any consistent lag pattern that could be interpreted as being density dependent.

A strong correlation between year-class success and good hydrographic conditions was found for all tested estuaries -- accounting for 72% of striped bass stock variability in the Potomac estuary, 26% in the Delaware estuary, and 79% in the Hudson-Raritan system. This is no surprise as it has long been recognized that there was good correlation between high year-class success and below-normal temperatures during the period directly preceding and following spawning (Pearson, 1938; Merriman, 1941; Vladykov and Wallace, 1952; Setzler et al., 1980). The success of striped bass year-class strength also seems to be highly correlated with freshwater flow (Chadwick, 1964; Stevens, 1977). A critical factor for egg survival is sufficient current velocity to keep the egg suspended in the water column (Talbot, 1966; Bain and Bain, 1982). River discharge can provide sufficient water movement to suspend the eggs. A minimum average velocity of 30 cm/s is necessary to prevent the concentration of eggs on the bottom (Albrecht, 1964). In the last 30 years, several investigators have reaffirmed these findings concerning hydrographic influences. They have provided a preponderance of evidence for environmental effects on year-class dominance (Merriman, 1952; Mansueti, 1961a; Clark, 1967; Koo, 1970; McHugh, 1972; Van Winkle et al., 1979; Ulanowicz and Polgar, 1980). General survival of eggs and larvae is associated with a fairly narrow threshold response to hydrographic and meteorological conditions (Eldridge et al., 1981; Setzler-Hamilton et al., 1981). The models presented here conform to and reaffirm their findings. In the target estuaries, striped bass stock abundance is clearly and consistently associated with freshwater discharge and temperature during the spawning season. In addition, a longitudinal trend is hinted by the finding that Potomac stocks spawn 3-4 weeks earlier than Delaware stocks and 3-6 weeks earlier than Hudson-Raritan striped bass.

A number of investigators have postulated about the influences of anthropogenic activities on the year-class success of striped bass. Mansueti (1961a) noted that sedimentation, pollution, wetlands reclamation, dams, pesticides, and radioactivity may have deleterious effects on striped bass populations. Conversely, he also postulated that eutrophication may be responsible for Chesapeake Bay's especially large dominant year classes. McHugh (1972) and Menzel (1973) have suggested that striped bass have increased in abundance in response to higher salt loads and associated higher nutrient levels. This notion is supported by Tsai (1984) who suggests that striped bass success in the Potomac is directly related to the magnitude and nutrient level of sewage effluents. He contends that the implementation of secondary treatment at the Blue Plains facility in the Potomac was in fact deleterious to the survival of striped bass larvae. Inspection of his analytical results clearly show that the source of variability in stock production is variation in Potomac River freshwater discharge and not sewage effluent. However, it is still not clear whether flow acts upon early life stages directly or as a method of dispersing a supply of food to zooplankton (the eventual food source for larval striped bass). However, regardless of this potential for a positive relationship between striped bass and nutrient loading, recent evidence suggests that toxicants, particularly polychlorinated biphenyls and monoaromatic hydrocarbons, and aluminum concentrations associated with runoff from acidic precipitation can significantly increase the mortality rates of larvae (Durham, 1980; Eldridge et al., 1980; Whipple et al., 1980 a,b; Mehrle et al., 1984; Hall, 1984).

The models presented here for striped bass stocks show that anthropogenic influences contribute a small but significant amount to variation in stock abundance in the Hudson systems and a larger and significant amount to that in the Delaware. No anthropogenic variables were significant for Potomac River striped bass. The abundance of Delaware stocks is positively associated with dissolved oxygen concentrations in the river. Some authors suggest that low dissolved oxygen concentrations (2.0-3.5 mg/l) are responsible for the absence of eggs and larvae in the Delaware River (Murawski, 1969; Chittenden, 1971). In fact, Turner and Farley (1971) reported that even moderate reductions in dissolved oxygen concentrations could decrease survival rates of eggs and larvae.

With the possible exception of the sizes of striped bass stocks in the Delaware Basin, striped bass stock sizes appear to be unassociated with anthropogenic influences other than fishing. As a result, no hypotheses can be generally determined for striped bass; although it seems plausible to pose a hypothesis that positively relates regional striped bass stock abundance and water quality in the Delaware River.

While no specific striped bass stock exists for the Narragansett Bay region, we analyzed a hypothetical Rhode Island stock based on Rhode Island landings by first comparing it to hydrographic and anthropogenic variables in Narragansett Bay. As expected, the model fits were poor, suggesting that the striped bass offshore of Rhode Island are little affected by Narragansett Bay's climatic or pollution conditions. Examination of the Narragansett "stock" in relation to hydrographic conditions in the Potomac and Hudson revealed that approximately 78% of the Narragansett "stock" variability could be explained by Potomac and Hudson conditions lagged appropriately. This 78% could be decomposed to 48% accounted for by Potomac River flow and temperature and 30% accounted for by Hudson River flow and temperature. These results agree with Berggren and Lieberman (1978) in that Chesapeake stocks appear to contribute more strongly to the Atlantic stock of striped bass than do the Hudson River or Roanoke River stocks.

6.1.3 Other stocks

The models constructed for alewife stocks in northeastern estuaries were generally poor ($R^2 < 0.50$). No stock relationship was established for alewife in any of the target estuaries except the Delaware River estuary, where lagged stock accounted for 11% of stock variability from 1933 to 1976. This finding disagrees with Havey (1973) who reported a strong correlation between the number of juvenile alewives produced and the number of adults returning four years later. Generally, alewife stocks are not dominated by year classes, and extensive offshore harvests in the period 1955-1975 may have reduced whatever stock dependence was inherent in the stocks (Richkus and DiNardo, 1984).

The onset of spawning for alewives is associated with temperature (Marcy, 1976) and usually occurs earlier at southern locations. The proposed models show that alewife stocks are significantly related to water temperature during spawning periods, except in the Potomac River, where alewife stock size was related to freshwater discharge.

Alewife stock sizes were weakly related to anthropogenic factors in two of the four target estuaries. Alewife stocks were negatively related to sewage discharges and 5-day BOD levels in the Potomac River. A number of fish kills occurred in the Potomac River in the 1960's as a result of dissolved oxygen depletions. After construction and implementation of secondary sewage-treatment facilities at the Blue Plains Sewage Treatment Plant in the late 1950's and early 1960's, the frequency and severity of oxygen depletions were decreased.

Atlantic tomcod are commercially fished only in the Hudson-Raritan system and not in the other target estuaries of the program. The model used to characterize the variability of Atlantic tomcod stock sizes in the Hudson River shows that the size depends strongly on January temperature and April flow, which together account for 69% of stock variation. Low temperatures during the spawning season (December-February) affect the hatching rate of deposited eggs (Scott and Crossman, 1973; Hardy and Hudson, 1975). Larvae are pelagic and are transported downstream by freshwater discharge until April (Howe, 1971; Booth, 1967) when they become self-sufficient.

Tomcod stock sizes are strongly associated with dredging activity in the upper Hudson River, but only if taken in conjunction with hydrographic conditions. This combination of low dredging activity, high stock levels, high January temperatures, and high April flows contributes significantly greater than average recruitments to future stock levels. A hypothesis concerning anthropogenic influences on Atlantic tomcod stocks that can be drawn from these analyses is that tomcod stock success in the Hudson River is related to the combination of environmental conditions delineated above.

The models gave poor results when applied to characterizing the abundances of Atlantic sturgeon in the three estuaries where they are fished commercially (the Potomac, Delaware, and Hudson). Sturgeon stocks could not be related to any hydrographic variables in either the Potomac or Delaware Rivers. Sturgeon stock abundance in the Hudson River was related to April temperature, which is consistent with available information concerning sturgeon in the Hudson River (DiNardo et al., 1984). However, few if any fishermen have directed their efforts toward harvesting sturgeon in the Hudson, and any reported landings are usually as bycatches of the gill net fishery for shad (Brandt, 1983). Thus, the calculations of the abundance of Atlantic sturgeon stocks after 1935 may be inaccurate.

Significant numbers of Atlantic sturgeon were fished in the above three estuaries prior to the period when landings data were collected consistently (i.e., 1929). The widely reported decline in Atlantic sturgeon landings in the early 1900's is often attributed to the over-exploitation of young and adult sturgeon as well as the incidental destruction of young sturgeon in other fisheries such as the shad pound-net and gill-net fisheries (Hildebrand and Schroeder, 1928; Dovel, 1976).

An active commercial fishery for smelt exists only in the Narragansett Bay/Rhode Island Sound region. Smelt is an inshore fish generally found in a narrow zone along the coast (within one mile of shore)(Bigelow and Schroeder, 1953). Adults generally run to freshwater to spawn in March or April in the northeastern estuaries, and the Narragansett smelt stock is related to April temperatures. In general, the model constructed for smelt has a poor fit, and no hypotheses relating smelt stock variability to anthropogenic influences are warranted at this time.

6.2 Resident Fisheries

The resident fisheries examined in this study include white perch, oyster, hard clam, and soft clam.

6.2.1 White perch

White perch is a relatively cosmopolitan species that inhabits rivers, bays, and estuaries from Nova Scotia to South Carolina (Leim and Scott, 1966). In general, the models constructed for white perch stocks in the target estuaries showed somewhat conflicting results. The Delaware stock model explained 84% of its variability; the Potomac model, 55%; and both the Hudson and Narragansett models, less than 35%.

White perch stock size was significantly related to previous stock levels in all target estuaries. The magnitude of this relationship was generally small, suggesting that while there may be some stock dependence inherent in white perch stocks, in general they are stock independent and controlled largely by environmental variation (Mansueti, 1961b; St. Pierre and Davis, 1972). There are few fisheries directed at white perch (Richkus et al., 1980). Most white perch landings are bycatches of fisheries directed at striped bass and American shad. As a result, different lag structures were required in each target area, depending on the fishery (e.g., striped bass, shad) in which the white perch were caught.

In all target estuaries except Narragansett Bay, white perch stocks were strongly associated with hydrographic conditions in April and May. While the relationship was generally to temperature in most estuaries, white perch stock abundance in the Potomac River was more strongly related to freshwater discharge than temperature ($R^2 = 0.55$). This agrees well with previous findings for the Potomac River (Summers et al., 1982), Virginia tributaries of the Chesapeake Bay (St. Pierre and Davis, 1972), Delaware River (Wallace, 1971), and the Hudson (Bath and O'Connor, 1982). In both the Potomac River and the Delaware River, white perch stock variation was best explained by natural variation in hydrographic conditions; 55% and 82%, respectively. No significant relationship to anthropogenic influences was determined for these two fisheries.

Mansueti (1961) speculated that low dissolved oxygen concentrations and high nutrient loads could negatively affect the year-class success of white perch and could override the density-dependent mechanisms inherent in white perch stocks. These relationships were also inferred by St. Pierre and Davis (1972) and Wallace (1971). The present investigation found that white perch abundance was positively related to dissolved oxygen levels in the Hudson River combined with April temperatures ($R^2 = 0.36$). White perch stock variation was also related to anthropogenic trends (e.g., sewage loadings, acreage in improved farmland) in the Narragansett Bay region. White perch appears to be generally much less affected by anthropogenic influences than by hydrographic factors.

6.2.2 American oyster

The recruitment of oysters into fishable stocks is known to be related to the lagged success of spat setting (Koganezawa, 1972). While this indicates a potential relationship between year-class success (spat-setting) and eventual recruitment into the oyster fishery, it does not imply stock dependence. This lack of relationship between adult stock sizes and lagged stock abundance is supported by the present analyses, which found that stock associations were not significant for oysters in the Potomac estuary and Hudson-Raritan region, and minimally significant ($R^2 < 0.10$) for oysters in Delaware Bay and Narragansett Bay.

Spat production appears to be density-independent and controlled by hydrographic conditions and predation (Ulanowicz et al., 1980; Krantz and Merritt, 1977). In all target estuaries, oyster stock variation was strongly related to hydrographic conditions. Ulanowicz et al. (1980) found that oyster spat success was related to salinity and rainfall patterns, while Lough (1975) found that larval survival rates were largely controlled by salinity and temperature interactions. In the present investigations, we found that historical oyster stock variation was associated strongly with freshwater discharge (Ulanowicz et al., 1980, did not test flow as a variable) and temperature. Beaven (1946) and Engle (1946, 1955) have shown a relationship between lagged river discharge and the subsequent setting of oyster spa. Generally, in the proposed models, summertime hydrographic conditions could be used to explain 47% to 60% of the observed variation in oyster stock size in the target estuaries.

Historic oyster stock abundance was significantly related to anthropogenic influences in all target estuaries. In the Potomac estuary, oyster stock size was positively related to 5-day BOD, and when combined with August temperature and June flow, accounted for 77% of the observed historical variation. Oyster stock size in the Delaware estuary was also strongly related to dissolved oxygen concentrations. When combined with hydrographic conditions, this positive relationship with dissolved oxygen concentration can account for 65% of observed stock variation. Dissolved oxygen conditions are believed to affect the ability of oyster larvae to maintain swimming patterns and to set successfully (Holland, personal communication, 1984). Oyster stock variation in the Hudson-Raritan estuary was associated with BOD loadings in Raritan Bay (i.e., due to treated sewage effluent). While this relationship was weak, it was significant and accounted for 54% of observed stock variability when combined with August temperature and August freshwater discharge. Clearly, a relationship exists between oyster abundance and water quality as represented by dissolved oxygen levels. We hypothesize that American oyster stock size is positively related to dissolved oxygen, and that historic declines in oyster stocks are caused in part by dissolved oxygen levels.

We did not quantitatively analyze an additional potential cause for recent oyster declines: an epizootic in oysters, caused by a haplosporidian parasite (*Minchinia nelsoni*, commonly called "MSX"). This disease has drastically altered oyster and other shellfish communities in Delaware and lower Chesapeake Bay. It was discovered in Delaware Bay in 1958 (Haskin et al., 1966) and had nearly destroyed the oyster industry there before it was found in the moderate- and high-salinity waters in Chesapeake Bay (Andrews, 1968; Andrews and Wood, 1967). In Chesapeake Bay, this disease has reduced harvests and led to poor recruitment during the 1960's (Sindermann, 1968). The incidence of MSX and its effects in the Delaware estuary are clearly depicted in Figure 68, which shows that oyster stock size plummets in 1958 and does not fully recover until 1973. Since salinities in the Potomac estuary are not generally favorable for MSX (i.e., > 15% ppt), the detrimental effects of MSX are not clearly seen there. Stocks in the Hudson-Raritan region were so reduced by 1960 that it is unlikely that MSX significantly affected that stock.

6.2.3 Hard clam

Hard clam populations are essentially stock-independent, and their variations in year-class success are generally attributed to environmental conditions and/or overharvesting (Ritchie, 1976). The present investigations support this finding, as no lagged stock relationship was found for Delaware Bay, and minor relationships ($R^2 \approx 0.15$) were extracted from time-series data on hand clam stock abundance in the Hudson-Raritan area and Narragansett Bay.

Environmental conditions affect not only the success of spawning, but also the subsequent survival and growth of larval and juvenile hard clams

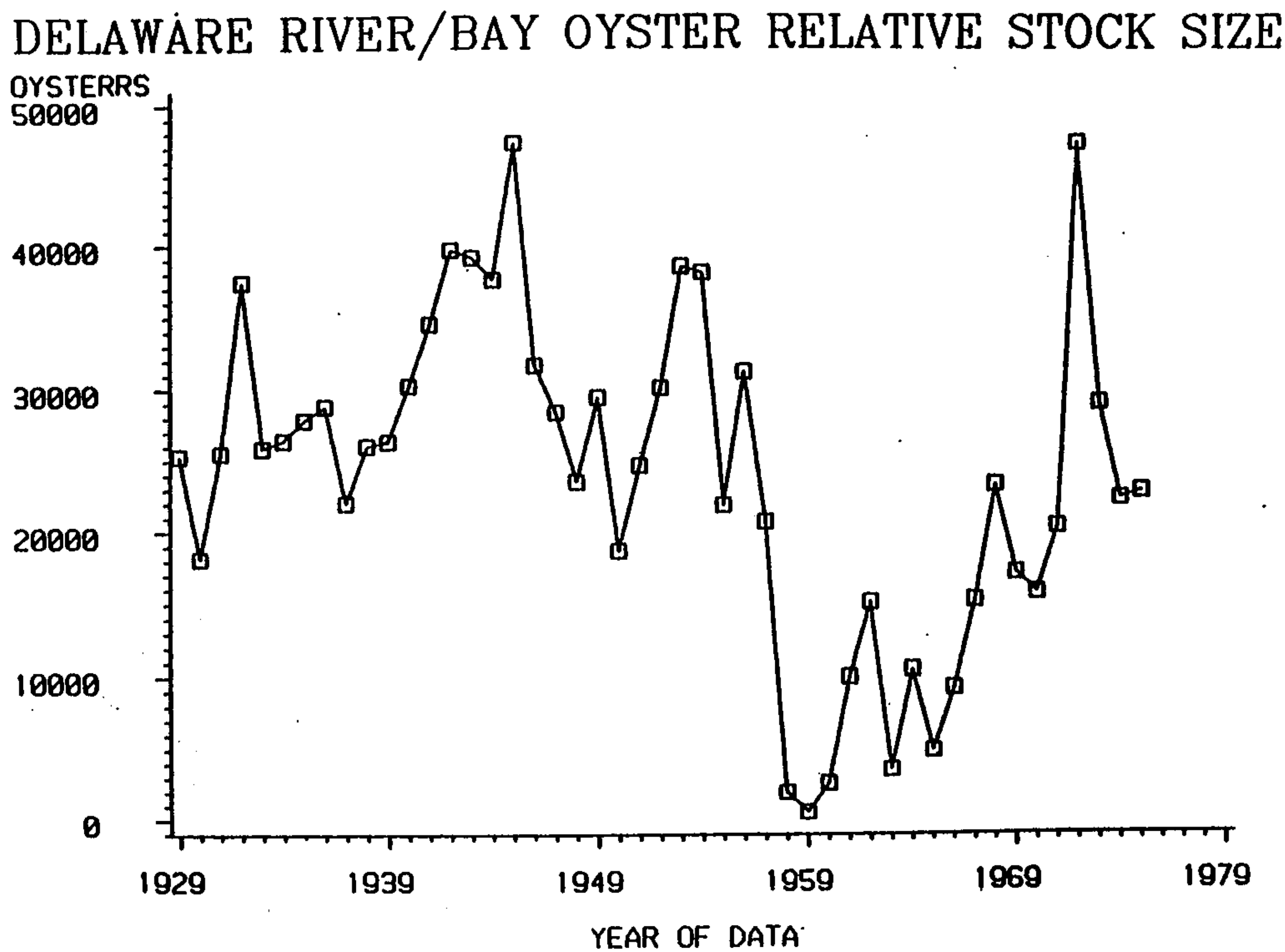

Figure 68. Relative stock index of American oyster in the Delaware estuary

(Ritchie, 1976; Pratt and Campbell, 1956; Wells, 1957; Eldridge et al., 1976). Variability in hard clam stocks was strongly related to summer hydrographic conditions regardless of location. Year-class success has been related to temperature, particularly during summer months (Wells, 1957; Pratt and Campbell, 1956). No relationships were found between growth rates and freshwater discharge by Pratt and Campbell (1956), but associations between discharge and juvenile clam distributions were noted by Wells (1957).

Our results suggest that abundance of hard clam stocks is primarily controlled by hydrographic events and that no anthropogenic sources of variability could be used to explain stock variation beyond natural events. This hypothesis runs counter to the prevailing view concerning the effects of pollutants on hard clams. Those holding this view speculate that water pollution from industrial (e.g., PCBs and heavy metals) and domestic (e.g., sewage) sources is a major problem confronting the hard clam industry (Ritchie, 1976). Under the National Shellfish Sanitation Program, molluscan shellfish can be harvested only from approved or conditionally approved harvesting areas. This approval is based on measures of bacteria in the water. Long-term time-series data on fecal coliform in the target estuaries were not available for the present study. While many projections concerning the negative effects of pollutants on landings exist (i.e., closure of beds and resulting reduction in effort), no conclusive evidence was found in the present study linking anthropogenic influences with reductions in stock size or condition. Cooper et al. (1964) examined stock sizes and conditions of quahog populations in upper (relatively polluted) and lower (relatively unpolluted) Narragansett Bay. Quahogs were far less abundant in cleaner waters, although this can be attributed to greater fishing intensity in the lower Bay. The condition (i.e., meat volume) of quahogs above and below the pollution line differed little. Studies of stock sizes in other regions (Sandy Hook, Delaware Bay) could not show that stock abundance had been negatively impacted by pollutants, although selected beds had been closed to active fishing (Tiller et al., 1952). According to our analyses, abundances of hard clam stocks appear to be controlled almost completely by hydrographic factors.

6.2.4 Soft clam

Commercialization of soft clam resources began around 1850, and demand was met completely by New England clam fisheries until World War II. Maryland's extensive sub-tidal soft clam populations were not fished commercially until the development of the hydraulic escalator dredge. The combination of this invention and the inability of New England sources to meet national demand forced Maryland into the forefront of this clam industry. The Maryland clam industry dominated the national harvest from 1956 to 1970. In 1972, severe flooding due to tropical storm "Agnes" caused extensive mortalities in existing soft clam resources in Maryland, and the industry was closed temporarily (Ritchie, 1976).

A significant lagged-stock relationship was extracted for stocks of Hudson-Raritan soft clams ($R^2 = 0.44$). No significant lagged-stock relationships were found in the stock-abundance histories of soft clams in the Narragansett or Potomac estuaries. Brousseau (1978 a,b) and Pfitzenmeyer (1962) found no relationship between adult population size and lagged juvenile spat set. The strong stock dependence elicited from the Hudson-Raritan records may reflect cycles in catch due to cycles in demand. The Hudson-Raritan soft clam fishery responded to increased national demand when New England fisheries could not meet that demand. Normally, this type of artificial cyclicity could be accounted for by correcting for fishing effort, but Raritan Bay clammers generally maintained gear licences throughout the period in case demand increased (Ritchie, 1976). Much of this "increase" in demand was due to poor recruitment in New England stocks due to predation by the green crab (Carcinus maenus). In the Gulf of Maine, cycles in green crabs have roughly paralleled depletions of clam resources (Welch, 1968; McHugh, 1977). Green crabs have been observed to reduce local soft clam populations by 90% (Welch, 1968).

Excluding predation, year-class success of soft clams is controlled primarily by environmental factors, although those factors are poorly understood (Ritchie, 1976). Populations north and south of Delaware Bay react somewhat differently to hydrographic conditions. Northern populations spawn continuously, with a peak in the early summer months (June-July) (Brousseau, 1978b). Maryland populations peak in late spring (May-June) and have a secondary peak again in the fall (October-November) (Pfitzenmeyer, 1962). The results of the present investigation clearly show this dichotomy and make apparent a longitudinal gradient for the Hudson-Raritan to Narragansett regions and a biomodal temperature relationship in the Potomac Estuary. Recruitment success is related to lagged temperature during periods of peak spawning and spat settlement, which can generally account for 40% of the observed historical variation in abundance, regardless of location. The finding that temperature is the overriding hydrographic variate agrees with previous findings (Pfitzenmeyer, 1962; Brousseau, 1976 a,b).

As for hard clams, some speculate that the abundance of soft clam stocks is related to pollution levels. Many harvesting areas are closed due to domestic and/or industrial loadings. With these closings, true stock abundances may not be clear since reductions in harvestable areas may lead to declines in landings. Only in the Hudson-Raritan region were soft clam abundances related to water quality (i.e., positively related to dissolved oxygen concentrations). Abundances in the Potomac and Narragansett estuaries were related positively to dredging activity, which as described previously, might be due to increased creation of favorable habitats. Kaneko et al. (1975) found some indirect evidence of microbial infection of Maryland soft clams, particularly in relation to sewage loadings, but these findings were not consistent over time. Our results are inconsistent with respect to the anthropogenic variables examined.

In recent times (i.e., post-1958), some soft clam harvest areas were closed due to paralytic shellfish poisoning (PSP). Areas in eastern Maine have been closed periodically through the 1970's as a result of Gonyaulax tamarensis blooms. These red-tide blooms have caused extensive damage to the fishery, but not generally to stock size. This potential influence on stock abundance was not examined in this study because red tides that cause PSP seldom occur in the targeted estuaries.

6.3 Ocean/Estuarine Fisheries

Many of the major commercial fisheries of the northeastern United States are supported by fish and shellfish stocks that spawn in coastal or open ocean waters and at some early stage in their development utilize estuaries as nursery and/or feeding grounds. These stocks include flounders (summer, winter, and windowpane flounders), spot, Atlantic croaker, weakfish, blue crab, American lobster, American eel, menhaden, bluefish, and butterfish. Each of these stocks is discussed below in relation to its historical associations with hydrographic factors and anthropogenic influences in northeastern estuaries.

6.3.1 Flounders

Three species of flounder were examined in the present investigation -- summer flounder (fluke), winter flounder (blackback), and windowpane flounder (sand dab). Summer flounder provide significant landings for commercial fisheries in all three tested estuaries; winter flounder, in the Hudson-Raritan and Narragansett estuaries; and, windowpane flounder, only in the Narragansett/ Rhode Island Sound region.

The analytical results for summer flounder were mixed and showed little agreement across estuaries. In the data from estuaries other than Delaware Bay, no significant relationship was seen between present stock abundance and lagged abundance. However, in the Delaware Bay, 31% of stock variability for summer flounder could be explained by lagged stock. In addition, no hydrographic variables could be related to fluke stocks in the Potomac and Hudson-Raritan estuaries. Although there was a relationship between the stock level of summer flounder and 5-day BOD levels in the Potomac River, we were essentially unable to model this relationship with data from either the Potomac or Hudson-Raritan estuaries. Both locations have viable commercial fisheries for this species (although the Hudson-Raritan fishery is marginal), and there is no apparent reason that correlative associations could not be found other than the potential for inappropriate test variates. However, the same procedure for choosing variates was used in the Delaware and Narragansett estuaries with excellent results; namely, strong associations were indicated between stock abundance and the period of time young flounders would be feeding in estuarine waters (May-August)(see Werme et al., 1983).

Fluke abundances in the Delaware Bay were strongly associated with late spring flows (May), which in combination with lagged stock accounted for 68% of stock variation from 1929 to 1976. As would be expected, stock abundance in Narragansett was related to hydrographic conditions somewhat later in the season (June and July). These conditions accounted for 41% of observed stock variability. In both cases, these associations probably relate not to the specific hydrographic conditions but to some correlate involving prey availability or abundance (primarily juvenile benthos and small fish).

In the Delaware, Narragansett, and Potomac estuaries, variation in the size of summer flounder stocks was related to anthropogenic influences. Stock abundance in the Delaware was positively associated with dissolved oxygen concentrations. This macropollution variate accounted for an additional 10% of the stock variation. Stock size of fluke in Narragansett Bay was strongly related to both anthropogenic trends (e.g., human population, acreage in improved farmland, sewage loading) and dredging activities in the bay, with each influence accounting for an additional 48% and 30% of stock variation, respectively. Little research has been conducted relating flounder abundance and the removal of dredged material, although Sissenwine and Saila (1974) found no negative relationship between fluke landings and dredge spoil disposal.

Unlike the results for summer flounder, those for winter flounder were more consistent. The present study revealed a significant relationship ($R^2 \approx 30\%$) between lagged stock abundance and present stock levels in both the HudsonRaritan and Narragansett estuaries. Howe et al. (1976) shows a relatively strong relationship between recruitment to the commercial fishery and production of juveniles two to four years earlier. Spring temperatures and freshwater discharge conditions are important contributors to winter flounder stock variability in both the Hudson-Raritan estuary (April temperature) and Narragansett Bay (March flow and temperature). Winter flounders disperse from shoal breeding grounds in response to rising water temperature (i.e., spawning discontinues), and the extent of their movement apparently depends on the proximity of waters with favorable temperatures (Coates et al. 1970). In addition, since larval utilization of prey is more efficient at warmer temperatures (Laurence, 1977), springtime thermal conditions may influence juvenile stock size.

Local stock size of winter flounder was positively related to anthropogenic trends in the Narragansett region and to dissolved oxygen levels in the HudsonRaritan estuary. While the trend relationship in Narragansett Bay bay simply show an increased demand for blackback, it may also indicate that additional organic loading to the sediments subsequentLy supports benthic organisms suitable for ingestion by juvenile winter flounder.

No relationships were found among present stock levels, lagged stock, hydrographic variables, or anthropogenic influences for windowpane flounder in Narragansett Bay. This fishery is not well known. Until recently this species was considered a "trash" fish (Olsen and Stevenson, 1975; Grosslein and Azarovitz, 1982), although it is presently taken for fishmeal.

While the results were mixed for flounders, three hypotheses can be forwarded relating to fluke and blackback.

- Summer flounder stock abundance is positively related to water quality (i.e., dissolved oxygen).
- Summer flounder stock abundance is positively related to dredging activities.
- Winter flounder stock abundance is positively related to water quality (i.e., dissolved oxygen).

6.3.2 Spot and croaker

A consistent significant relationship ($R^2 = 0.15$ to 0.22) was found between the abundance of spot stocks and lagged stock in the Potomac, Delaware, and Hudson-Raritan estuaries. No support for this alleged stock dependence was found in the scientific literature. However, it has been suggested that Atlantic Coast spot represent one massive spawning population (Grosslein and Azarovitz, 1982; Fahay, 1975). Thus, if the entire spawning stock and subsequent spawn are exposed to similar environmental conditions, then a pseudostock dependence might be displayed.

Spot generally spawn in offshore waters in late fall and winter, with the young appearing in estuaries of the middle and southern Atlantic states in December (Weinstein and Walters, 1981). In our models of spot abundance in the Potomac and Delaware estuaries, the year-class success was strongly related to December wind conditions. The implication is that winds from the northwest to southwest quadrant create counterflows into the Chesapeake Bay or Delaware Bay in non-surface coastal waters, which in turn assist young-of-the-year into the mouth of Chesapeake Bay or Delaware Bay from ocean waters (Norcross and Shaw, 1984). Although these relationships explain only an additional 10% of stock variance in each of the estuaries, the finding is consistent in mid-Atlantic estuaries. Unlike that of the Potomac and Delaware estuaries, stock abundance of Hudson-Raritan spot was related to hydrographic conditions in spring (April). This relationship is not inconsistent with the earlier findings, but suggests that the Hudson-Raritan region is not a prime area for development of young-of-the-year. Adults and large juveniles return to estuarine waters in April and May rather than in earlier months (Pacheco, 1962). In addition, spot fishery patterns have changed drastically in the Hudson-Raritan area over the period studied in our investigation. In 1925, spot were so abundant off of New York that the Brooklyn Edison Company was forced to shut down its generators in order to remove spot from condenser pumps (Nichols and Breder, 1927). However, their abundance declined drastically from the late 1940's through the early 1970's (McHugh and Ginter, 1978). This change in stock abundance may simply reflect a shift in geographic distribution, because spot is near its northern limit (i.e., sufficient to support a consistent spot fishery) at the Hudson-Raritan estuary.

It has been hypothesized that degradation of estuaries from industrial and residential development and pollution may have had a deleterious effect on the survival of junvenile spot (Joseph, 1972). No detrimental effects of anthropogenic influences were determined from our analyses. Only dredging actvity in the Hudson-Raritan region was related to spot abundance, and that relationship is weakly positive. Increased dredging activity could possibly result in increases in the benthic organisms that are the prime food items of juvenile and adult spot.

Results for Atlantic croaker in the Potomac and Delaware estuaries indicate a strong relationship ($R^2 \approx 0.30$) between croaker abundance and lagged stock size, suggesting some stock dependence. This dependence is likely an artifact of the analysis, as lags of only 1-3 years (particularly 1 year) introduce rapid historic memory to the stock (i.e., if the stock size is large in one year, it is likely to be large in the next). Evidence of stock dependence for Atlantic croaker is very weak (White and Chittenden, 1977).

Atlantic croaker spawn offshore over a protracted period extending from September to March, with a distinct spawning peak about October (Grosslein and Azarovitz, 1982). The success of Atlantic croaker in Delaware Bay was strongly associated with coastal wind conditions in October, which accounted for 67% of stock variation when combined with lagged stock. As for croaker in the Delaware estuary, a significant relationship of croaker abundance to October wind was found for Chesapeake Bay croaker, but December temperature conditions in the Potomac River could account for more stock variability (47%). Joseph (1972) concluded that temperature is a dominant factor controlling young-of-the-year stock size for Atlantic croaker once the fish are within the estuary. Mass mortalities of young-of-the-year croakers have been observed during very cold winters in the Chesapeake Bay (Chao and Musik, 1977).

A positive relationship was found between croaker abundance in the Potomac estuary and dissolved oxygen concentrations. This positive association is unsupported by findings reported in the literature, although young-of-the-year are generally present in the lower Potomac River during summer months. Natural hydrographic events appear to play dominant roles in the variability of these stocks.

6.3.3 Weakfish

It has been postulated that stocks of Atlantic coast weakfish may be composed of two or three distinct populations, but the evidence is only suggestive (Perlmutter et al., 1956). The current analyses may lend some support to this conjecture as stock dependency in this group seems to be geographically related. For the four target estuaries examined, weakfish appear weakly stock dependent at the northern and southern extremes (Potomac and Narragansett estuaries), but very strongly stock dependent ($R^2 \approx 0.53$) in the Delaware Bay and Hudson-Raritan region. A possible explanation for this geographic anomaly is that the Potomac River may be at the margin of the weakfish's furthest intrusion into Chesapeake Bay, while the Narragansett Bay may be close to its northernmost extent. In addition, there are no major weakfish fisheries at the geographic extremes (i.e., most of the catch is bycatch from efforts directed at other species), while both the Delaware and Hudson-Raritan regions have large weakfish fisheries. Thus, stock measures are relatively unaffected by effort in the northern and southern locations (i.e., landings and relative stock measures are correlated at about 0.97), while stock measures for weakfish in the mid-Atlantic region are strongly affected by effort directed at the fishery.

Very little is known about the factors affecting population size or recruitment of the weakfish. McHugh and Ginter (1978) hinted that observed historical fluctuations are probably due to natural variations in recruitment. Weakfish generally spawn in nearshore or estuarine zones along the coast from May to October and usually show peak spawning during May or June (Welsh and Breder, 1923; Yetman et al., 1984). Again, this relationship holds in the present investigation except at the geographic extremes. Weakfish stock abundance is strongly related to hydrographic conditions in both Delaware Bay and the Hudson-Raritan estuary. In the Hudson-Raritan region, the abundance of eggs spawned nearshore or in New York Harbor are related to wind conditions in May. Inappropriate conditions (i.e., winds from the NE to SW) could propel the buoyant weakfish eggs oceanward. Possibly for similar reasons, weakfish stock abundance in the Hudson-Raritan area is negatively related to freshwater discharge in June. The combination of lagged stock and these hydrographic factors accounts for 75% of weakfish variability in the Hudson-Raritan. This same negative relationship between flow and stock size is seen during the spawning period (April) in Delaware Bay. In the outer geographic reaches of its range (Potomac River), weakfish stock size is related to July temperature. This relationship makes sense for the Potomac River since peak May or June spawn for lower Chesapeake Bay would not reach the Potomac River until late June or July.

Little or no information concerning weakfish sensitivity to anthropogenic effects is available. The results of our analyses of the relationship of stock variation to anthropogenic variables are inconsistent across estuaries. Significant relationships between weakfish abundance and anthropogenic variates were found for all estuaries except Delaware Bay, but these variates were different for each estuary. Weakfish stock abundance was positively related to dredging activity in the lower Hudson-Raritan system. In conjunction with lagged-stock and hydrographic variables, dredging activity can account for 81% of the observed historic variation in weakfish stocks since 1929. This positive association may be related to the increase in habitat for food items (e.g., benthic worms) preferred by early life stages, which has been brought about by dredging activity (Thomas, 1971; Merriner, 1975). The Potomac weakfish stock is negatively related to biological oxygen demand associated with sewage loading, which could also relate to availability of preferred prey items. Relative stock abundance of Narragansett Bay weakfish increased drastically from 1970 to 1976 and is related positively to increasing anthropogenic trends (e.g., sewage loading, human population).

6.3.4 Lobster and blue crabs

Northern lobsters can generally be divided into inshore and offshore groups based on fishing methods and population characteristics, although some overlap exists (Skud, 1970). Results from studies undertaken to resolve the problem of stock identification generally support the above hypothesis (Saila and Flowers, 1968; Barlow and Ridgeway, 1969; Tracey et al., 1975; Uzmann et al., 1977). In our analyses, general stock dependencey was shown for all lobster "stocks" for those estuaries where lobsters occur (i.e., no lobster in Potomac estuary).

All analyses show that lobster stocks are very sensitive to temperature and are related to either March or April temperatures in all three target estuaries. Temperature accounts for 48% to 69% of observed stock variation. These findings agree completely with earlier investigations (Dow et al., 1975; Dow, 1964, 1969, 1976, 1977; Flowers and Saila, 1972; Orach-Meza and Saila, 1978). Cooper and Uzmann (1971) rarely found recaptured lobsters in regions with temperatures other than those between 10° and 17.5°C during spawning season. In fact, Saila and Flowers (1968) found that offshore egg-carrying females displaced to inshore waters did not appear to move offshore until the eggs had been shed.

Although there is no significant evidence to support the assumption (and, in fact, most literature indicates the opposite interpretation), facotrs other than temperature may cause fluctuations in lobster stock sizes (e.g., Flowers and Saila, 1972). Wilder (1952) found that heavy metals (e.g., copper, zinc, and lead) were toxic to lobsters. Pearce (1971) studied New York Bight benthic communities and found that all lobsters that migrated to waste disposal sites were debilitated and diseased. Studies (e.g., Young and Pearce, 1975) also showed that sediments in dumping zones were characterized by very high concentrations of heavy metals. Organic materials or chemicals that impose a high rate of dissolved oxygen depletion present threats to lobster stocks (Dow et al., 1975). In our analyses, lobster stocks in the Hudson-Raritan region were associated with dissolved oxygen concentrations. In the Narragansett Bay area, stock variability was strongly associated with anthropogenic trends (e.g., sewage loadings). Detergent and other cleaning agents carried into seawater from household or commercial laundry facilities are toxic to lobsters and may be a significant contributor to the "natural" mortality of local stocks (Dow et al., 1975). No relationships to anthropogenic influences were found for Delaware Bay stocks. This is not unexpected, as lobsters landed in the Delaware

Bay area are generally captured 50-100 miles offshore and are unlikely to be exposed to the dissolved oxygen or other pollution-related problems associated with this region.

Blue crabs are generally portrayed as an example of a stock-independent fishery in which a small number of females, contributing 2 million eggs each, could repopulate an entire region (Richkus et al., 1980). In our analyses, a small but significant lagged stock relationship was found in all target estuaries where blue crabs occur (i.e., few blue crabs generally occur north of Long Island, NY). This small relationship is not totally unexpected as the blue crab fishery is characterized by short lags (1-2 years), and with such lags, system memory can be quite strong.

Blue crab mating occurs during summer and early autumn (May-October). After insemination, females migrate to higher salinity and deeper waters (Darnell, 1959; Lippson et al., 1982) (e.g., mouth of Chesapeake Bay, Delaware Bay, Hudson-Raritan, or coastal waters). In this environment, eggs are fertilized and eventually released (Cargo, 1958). Our analyses of blue crab stocks suggest that wind conditions at the mouths of major estuaries are a major hydorgraphic variable affecting the year-class success of blue crabs. Wind conditions at the end of the spawning season (about August) of one year significantly affect the success of blue crabs in that estuary for the next two years. Our results are consistent for the Potomac and Delaware estuaries, where wind conditions account for 43% and 25% of the variability in stock size, respectively, for those estuaries. This finding agrees well with studies continuing in Chesapeake Bay (Johnson, 1982; McConaugha et al., 1982; McConaugha, 1983; Provenzano and McConaugha, 1980) that suggest that early blue crab larvae are flushed from the bay soon after hatching. Development takes place offshore, and the probability of return of zoeal and megalops stages to the Chesapeake Bay system is profoundly influenced by wind-driven surface currents.

Wind events appear less important in the Hudson-Raritan system according to the present analyses. While wind events were significant, they were overshadowed by hydrographic conditions during spawning (temperature and flow during June and July) and overwintering temperatures (February). These variables accounted for 55% of stock variability in the Hudson-Raritan area. Pearson (1948) suggested that excessively cold weather may reduce the subsequent availability of immature and male adult crabs and that river discharge and temperature were related to the spawning success of blue crabs.

The effects of anthropogenic influences on blue crabs are poorly understood, but it is believed that early life stages may be particularly vulnerable to water-borne pollutants. Clear links between the estuarine loadings of organic pesticides and the subsequent decline of blue crabs have been shown in the Hudson-Raritan region for DDT/DDE (McHugh, 1977) and in the James River for Kepone (Lippson and Gardner, 1977; Schimmel et al., 1979). This type of specific pollutant inflow was not examined in the present set of analyses. Examination of historic stock trends for blue crabs in northeastern estuaries showed a negative association between stock size and sewage loading in the Potomac River as well as a positive association between crab stock size and dissolved oxygen concentrations in the Delaware Bay.

6.3.5 Other ocean/estuarine stocks

Of the species that spawn in ocean waters and develop at some early life stage in estuarine regions, the remaining stocks investigated are eels, bluefish, butterfish, and menhaden. Results for all these species were inconsistent, but some good model fits were achieved for this group.

The American eel is somewhat different from the other members of the group of ocean spawners. Eels are catadromous -- spawning supposedly in the Sasgasso Sea and migrating back to "home" river systems as larval and juvenile forms. Very little study has been devoted to the American eel, and much about the species is inferred from knowledge about its European congener, the European eel (Helfman et al., 1984). Little or nothing is known about the potential for stock dependence in American eels (Hurley, 1972; Fahay, 1978). The present analysis extracted some significant stock dependence from relative stock-abundance time-series data in all target estuaries except Delaware Bay. Stock dependence generally accounted for 17% to 32% of historical stock variability.

Leptocephali, or eel larvae, are completely at the mercy of ocean currents moving northward along the Gulf Stream until they metamorphose into elvers. Elvers begin moving inshore in late winter or early spring as a result of local currents. Small numbers of elvers regularly arrive in estuaries several months before the main immigration in spring and summer (Fahay, 1978). The present investigation found similar timing for eels in all the target estuaries. Eel stock abundance was associated with spring or summer hydrographic conditions (generally temperature), which accounted for 10% to 58% of historical variations in stock size. Hiyama (1953) found that elvers were sensitive to significant thermal differences between offshore and nearshore estuarine waters.

Eels are very hardy and can live under a number of conditions provided they are kep moist and supplied with oxygen (Fahay, 1978). Historic abundance of eel stocks in the Potomac River is negatively associated with biochemical oxygen demand associated with sewage. This variable in conjunction with hydrographic factors and lagged stock accounts for 82% of the variability seen in eel abundance from 1929 to 1975. Eel stock size in the Potomac was also related negatively to dredging activity, which, in conjunction with hydrographic variables, accounts for 84% of variation. No attempt was made to simultaneously examine BOD and dredging volume as sources of variation because construction of a five-variable categorical model would have reduced the number of degrees of freedom in the model to an unacceptably low level. Weak negative associations between stock abundance and dredging activities were also extracted from data on eels in the Delaware and Hudson-Raritan systems. Eel stock abundance in the Narragansett Bay region was strongly associated (positively) with sewage loading in that area. Sewage effluents may provide substrate and food material for several of the benthic prey items preferred by eels (Wenner and Musick, 1975; Shaughnessy et al., 1984).

Bluefish spawn primarily during spring in the Southern Atlantic Bight, in summer in the mid-Atlantic, and to a lesser extent in fall and winter in offshore waters (Kendall and Walford, 1979). Larvae from the spring spawning are evidently carried northward in April and May and spread out along the mid-Atlantic continental shelf. Larvae spawned in summer generally remain in the mid-Atlantic region. As shelf waters become suitably warm, generally in mid June, young bluefish cross the shelf and enter estuarine waters where they spend the summer months (Norcross et al., 1974; Kendall and Walford, 1979). Results of the present analyses suggest that hydrographic conditions in June play a significant role in stock variability for bluefish in Delaware Bay and the Hudson-Raritan area, accounting for 67% and 36% of historic stock variation. August thermal conditions accounted for 70% of the variation in Narragansett bluefish stocks. This longitudinal shift is supported by Lund and Maltezos (1970) who found large numbers of bluefish arriving in southern New England estuarine waters during late July and August in response to warming temperatures.

Associations between bluefish stock levels and anthropogenic influences were only seen in the Husdon-Raritan region. A positive association between bluefish abundance and dissolved oxygen levels in New York Harbor accounted for 60% of historic stock variation when combined with lagged stock and hydrographic variables.

Two stocks of oceanic butterfish probably exist in the Atlantic. One population appears to be restricted to shoal waters south of Cape Hatteras, North Carolina, and another population occurs chiefly north of Cape Hatteras in deeper waters of the shelf (Caldwell, 1961; Horn, 1970). No information is available concerning the possible stock dependence of these species. The present analyses provided mixed results among estuaries, with no significant stock relationships extracted for the Potomac or Hudson-Raritan estuaries (where little or no spawning occurs) and significant relationships found for the Delaware Bay (30%) and Narragansett Bay/Rhode Island Sound (15%) regions (where spawning occurs).

Butterfish spawn chiefly during summer (June-August) in inshore waters. The times and durations of spawning are closely associated with changes in surface water temperature (Colton, 1972). Historic stock levels of butterfish were associated with hydrographic conditions in June and July in all estuaries except the Potomac, where butterfish rarely occur. Conditions in June and July account for 36% to 55% of the historic variation in butterfish in Delaware Bay and Narragansett Bay, respectively.

Butterfish are primarily an offshore stock except during spawning and early development. Spawning does occur in Delaware Bay up to river mile 20 or 30 and throughout Long Island Sound (Werme et al., 1983; Grosslein and Azarovitz, 1982). As a result, stocks would not be expected to be related to estuarine anthropogenic influences except in these spawninig areas. No relationships between macropollution variables and butterfish stocks were determined except in Delaware Bay. In this region, butterfish variation was strongly associated with dissolved oxygen concentrations (positive), which accounted for 51% of historic variability in conjunction with June freshwater discharge and lagged stock.

Menhaden appear to be one large Atlantic stock that intermingles offshore during spawning periods. As a result, little stock dependence would be expected, and analyses of target estuarine "stocks" show small significant relationships to lagged stock histories. Schaaf and Huntsman (1972) found a signifcant but weak Ricker spawner-recruit relationship for menhaden. Henry (1971) felt that no reliable relationship could be established between the spawning stock of menhaden and subsequent recruitment to the fishery.

Principal spawning occurs during late autumn and winter off the coasts of Virginia and the Carolinas (Kendall and Reintjes, 1975), although menhaden spawn along the entire Atlantic Coast. Larvae generally enter estuaries three to five weeks after hatching (Henry et al., 1965), being transported to inshore areas by wind-driven surface currents in the ocean or by swimming (Nelson et al., 1977). Adults and yearlings generally do not appear along coastal waters until April, and schools move northward toward Cape Cod until late August or September (Nicholson, 1971, 1972, 1978). The findings of the present analyses correspond to the above description of spawning distribution and seasonal movement. In Delaware Bay and Narragansett Bay, wind conditions in October and November created landward surface flow and accounted for 38% and 55% of historical variation in menhaden stocks, respectively. Potomac and Hudson-Raritan "stocks" were more closely related to temperature conditions during periods when immature and adult menhaden arrive; but in both cases, only a small amount of stock variance was explained (<25%).

Dredging and filling, domestic and industrial wastes, and the effects of urbanization have been suggested as causes for reductions in the menhaden's estuarine nursery areas in the northeastern United States (Spinner, 1969). Spinner estimated that 10% to 30% of coastal marshes (which serve as menhaden nursery areas) were lost between 1954 and 1968. In the present analyses, we could find no relationship in any target estuary relating menhaden stock variation and anthropogenic influences.

The decline in menhaden landings in all target regions probably was due primarily to a series of poor year classes in the late 1950's and early 1960's. Overfishing did not cause the initial decline as was once believed (Henry, 1971), but there are strong indications that reduced stocks may subsequently have been overfished as a result of changes in fishing technology used by American and foreign fleets. This overfishing may have contributed to the continued reduced abundance and the failure of the fishery to recover.

6.4 Ocean Stocks

Of the 15 ocean stocks originally targeted for analysis (see Chapter 1), only two appear to actively use inshore regions. These stocks are scup and tautog. Scup was analyzed from Delaware northward and tautog was analyzed for the Hudson-Raritan and Narragansett Bay regions.

6.4.1 Scup

It is not clear whether there is one homogeneous population of scup in the mid-Atlantic or whether there are separate stocks. From tagging and meristic studies north of Delaware Bay, Hamer (1970) suggested there may be distinct subpopulations occupying areas off southern New England and New Jersey in the summer. Analyses relating present scup stock abundance to lagged abundance lend some support to this contention, as significant stock dependence ($R^2 >$ 0.25) was seen in each target estuary. In fact, 54% of historic variation in scup off Narragansett Bay can be explained by a lagged stock variable.

Scup spawn from about May through August, a period corresponding to the inshore migration of adult populations. Scup eggs are buoyant and contain a single oil globule (Bigelow and Schroeder, 1953). Newly hatched larvae are pelagic, metamorphosing to bottom dwellers when they become about 25 mm in length (Kuntz and Radcliffe, 1918). These characteristics of the scup's early phases (i.e., before metamorphosis) suggest that the stocks may depend on surface currents in the ocean to maintain their nearshore position. Analyses of historic stock records show that the Hudson-Raritan and Narragansett stocks are strongly affected by wind conditions during the spawning seasons which would maintain landward flow and temperature conditions. The Hudson-Raritan and Narragansett Bay regions are primary spawning grounds for scup (Neville and Talbot, 1964; Wheatland, 1956). Hydrographic conditions during the spawning period account for 70% to 85% of historical stock variation in these locations when combined with lagged stock variables. In Delaware, 52% of scup variation can be explained by August temperature and lagged stock. No wind variates explain the Delaware variation, but scup spawning generally does not occur south of Barnegat Bay, New Jersey, and metamorphosis probably occurs before young-of-the-year scup reach Delaware Bay.

No strong relationship to anthropogenic influences was found for scup regardless of location. A weak influence of dissolved oxygen in the Hudson-Raritan estuary was found. Scup are bottom feeders that consume small crustaceans, worms, molluscs, and some detrital material (Maurer and Bowman, 1975). Low dissolved oxygen conditions may result in the exclusion of some feeding grounds to juvenile scup or cause direct mortalities. A weak positive relationship to dissolved oxygen concentrations was also seen in Delaware Bay in conjunction with a negative relationship to anthropogenic trends (e.g., sewage loadings). These analyses suggest the hypothesis that scup populations may be negatively affected by poor water quality (e.g., low dissolved oxygen and high sewage loads).

6.4.2 Tautog

Tautog is a popular marine sport fish off Rhode Island and in Long Island Sound, but the commercial fishery for tautog is relatively small. The Rhode Island fishery was 2 to 3 x 10^5 pounds prior to World War II but declined to about 50 x 10^3 pounds afterward. The Hudson-Raritan fishery for tautog has historically been marginal, peaking in 1975 at approximately 70 x 10^3 pounds. Previous stock history explains 44% of the variation in the Narragansett Bay tautog stock, suggesting a strong stock dependence for this species although no significant stock relationship was seen in the Hudson-Raritan area (a marginal region for tautog spawning).

Tautog aggregate in Narragansett Bay to spawn in May and June (Cooper, 1966). In both estuaries, tautog stock variability was related to freshwater discharge in June, which accounted for 39% and 52% of variation in stock for the Hudson-Raritan and Narragansett estuaries, respectively.

No information is available on possible effects of anthropogenic discharges or activities on tautog stock size. Tautog stock variability was positively associated with dredging activity in the Hudson-Raritan system. Tautog is a bottom feeder whose diet consists almost completely of mussels (Olla et al., 1974). It is unknown whether dredging activities may increase habitat for these molluscs. In the Narragansett Bay region, 71% of stock variation can be explained by anthropogenic trends (e.g., human population, sewage) in conjunction with June flow and lagged stock.

7. CONCLUSIONS

As described in Chapter 2, the use of macropollution variables does not permit one to make any direct correlative associations between specific pollutants (e.g., lead, PCBs, DDT) and fish stock abundance. The pollution macrovariables, particularly dredging activity and dissolved oxygen levels, do allow some conclusions to be drawn concerning generalized relationships between these variables and fish stocks. Dredging activity and dissolved oxygen in the target estuaries display extensive short-term (year-to-year) variability. Thus, statistical associations to these two macropollution variables are intuitively more supportable than correlations to macropollution trend variables (i.e., monotonic trends like human population size, sewage loading, or employment). Of the 68 significant stock-pollution relationships found in this study, 26 were related to macropollution trend variables. As such, the results may or may not be due to the simple coincidence of increasing and decreasing trends in fisheries and pollution inputs. Unfortunately, the relationship may simply show a relation to some "untested" trend variable, which may be environmental or biological in nature rather than related to pollution.

The remaining 42 significant stock-pollution relationships offer more concrete evidence, although it is certainly not causal evidence. Analyses using two macropollution variables -- dredging activity and dissolved oxygen -- provide clear statistical statements of the hypothesized relationship between the macropollution variates and fisheries abundance. Dissolved oxygen concentration has been used as a general indicator of water quality in countless instances. Every significant relationship to dissolved oxygen, regardless of the specific estuary being analyzed, showed a positive association with fish abundance. The results of analyses of the relationship of oxygen to fish stocks identified a number of stocks (e.g., American shad, American eel, American oyster) and stocks in specific estuaries (i.e., half of the stocks in Delaware River/Bay) whose abundance is strongly related to oxygen levels, and by supposition, to water quality. This finding suggests a clear link, although not the mechanism, between stock success and water quality. Examination of historical time-series data on specific pollutant loadings, particularly for the Hudson-Raritan and Delaware estuaries, would help focus the generalized hypotheses about water quality made above and in Chapter 6.

From a different perspective, but perhaps just as interesting, is the consistent but weak relationship found between stock abundance in many fisheries and dredging activities, both within the spawning reaches of the target estuaries and throughout the entire estuary. Every significant relationship to dredging activity was positive except for American eel in the Potomac River and Atlantic tomcod in the Hudson River. This may indicate some complementary effect of this activity on stock success. As described earlier, many authors have supported the concept that high turnovers of population and increased biomasses (with time) occur in dredged and dredge-spoil regions as long as the spoil is not highly toxic (e.g., containing high PCB levels). Ten of the eleven stocks whose abundance was positively related to dredging activities are partial or complete demersal feeders or are shellfish for which dredging might create additional habitat. This relationship should be investigated further.

Examination of the stocks by functional category also reveals many patterns related to regional anthropogenic influences and stock success. All anadromous fisheries examined, except American shad, were strongly influenced by local hydrographic conditions (freshwater discharge, temperature) and weakly influenced by macropollution variables (except striped bass in the Delaware River). American shad declines in all target estuaries were more strongly associated with anthropogenic influences than climatic variation. In general, anadromous stocks were modeled well by the approach used in this program.

Resident estuarine species are exposed to local activities for their entire life span. As expected, the abundances of most resident stocks were related to anthropogenic activities, particularly those of American oyster and soft clams. Only hard clams were not associated with the gross "pollution" variables in any estuary. Hard clam abundances were, however, related strongly to climatic variation in a number of locations.

Of the 13 species in the ocean spawner/estuarine developer group, American eel stands out as an anomaly. The catadromous eel is a resident species within a basin for most of its life, and the strong relationship of its stocks to anthropogenic influences depict this association. The remaining stocks in this functional group are poorly related to negative anthropogenic influences in the target estuaries except for summer flounder, which are associated with generalized water quality in the two southernmost estuaries. The stock sizes of species in the ocean/estuarine group are clearly related to some positive effect on stock success associated with dredging. The abundance of approximately 65% of the stocks in this group is related to dredging activities in at least one of the target estuaries.

The abundances of the two primarily coastal stocks, scup and tautog, appear to become more related to anthropogenic conditions near the southern extents of their ranges. While both species are still plentiful in the Hudson-Raritan region, their abundance is rapidly reducing compared to abundances in Long Island Sound and Rhode Island Sound. The relationship of these stocks in the Delaware Bay or Hudson-Raritan estuary to macropollution variables may reflect some increased latitudinal stress resulting in susceptibility to local conditions. In the Narragansett Bay/Rhode Island Sound region, both stocks are well modeled using climatic conditions alone.

These results suggest that while there are exceptions (i.e., American shad, summer flounder), obvious relationships between historic stock abundance and gross indicators of pollution are best seen for estuarine resident fisheries and shell fisheries. Clearly, these analyses do not indicate that the remaining stocks are not affected by pollutant inputs, but simply that those associations cannot be determined using highly aggregated gross indicators of human activities (macropollution variables) in the river basins. Just as clearly, the results do indicate that the methodology does establish defensible links among stock histories, natural environmental variation, and macropollution trends that permit the generation of hypotheses pinpointing those stocks that are most likely to be affected by particular variates. Further examination of the stocks using specific loading histories for target pollutants will result in a substantial strengthening of the hypotheses that would relate stock variation and pollution loadings. This strengthening and eventual substantiation of proposed hypotheses are essential in any management plan for the prudent (ecological and/or economic) control of pollutant inputs to the nation's estuaries.

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